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ROYAL AIRCRAFT ESTABLISHMENT

FARNBOROUGH, HANTS

TECHNICAL NOTE No: R.P.D.39

INV 90

REPORT ON VISIT TO ESTABLISHMENTS
IN THE UNITED STATES DEALING WITH
LIQUID PROPELLANT ROCKET MOTORS,
APRIL - MAY, 1950

by

L.W.BROUGHTON, R.P.D., Westcott,

L.W.J.NEWMAN,

Sir W.G.Armstrong Whitworth & Co. (Aircraft) Ltd, Coventry

and L.A.WISEMAN, E.R.D.E., Waltham Abbey

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CDR. F. MAXWELL Jwm
Mr. T. Reinhardt TFR

This is an interesting report. The British agree that we are doing a lot of work, but yet they can't see anything they would like to copy. They point out quite vividly that the research and development people are working madly without any specific requirements from the application people.

The British point out that apparently our best bet is nitric acid and gasoline. However a great deal of effort is required to solve the long term storage problem of acid.

The British further, can't see why we are doing so much work on hypergolic systems. They prefer non-hypergolic systems.

The British have been sending a team over here every year. We have not to date sent such a team over with the exception of a small group in 1946. Suggest Baker have a representative(s) pay them a visit and find out what they are doing. A return visit would be welcomed by them, and we may save ourselves a lot of time and money. The British have done some good work on gas pressurization systems and monopropellants.

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September, 1950

2L ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

4L Report on a Visit to Establishments in the United States
dealing with Liquid Propellant Rocket Motors, April - May, 1950

5 by *and others*

L.W. Broughton, R.P.D., Westcott
L.W.J. Newman, Sir W.G. Armstrong Whitworth & Co. (Aircraft) Ltd.,
Baginton, Coventry.
L.A. Wiseman, E.R.D.E., Waltham Abbey

SUMMARY

This visit to the United States was made between 26th April and 24th May, 1950; the main purpose was to obtain information from the various establishments on the state of research, design and development of rocket motors based on nitric acid, although discussions on other oxidants took place as mentioned in the text of this Note.

Nothing outstandingly new was seen in actual rocket motor design, but there is no doubt that much work has gone into the design, development and production of ancillary equipment such as valves, turbines, pumps, pressurizing systems etc., and it appears that the United States research and development organizations could produce a very good operational rocket motor based on nitric acid, provided that the best ideas of these establishments were combined. The general conclusion of the mission is that, at the present state of development, the best all round design of nitric acid motor would include an impinging jet injector, a regeneratively cooled combustion chamber operating at a pressure of about 20 atm with propellant feed by either pressurized tanks or a turbo pump unit, depending upon the size of the motor.

The mission found it impossible in the short time available to form any really detailed conclusion on the state of rocket motor development, and recommends that technicians should be interchanged with American establishments to ensure continuous liaison. If this should prove impractical then at least one rocket motor engineer should be attached permanently to the B.J.S.M. to cover this type of work.

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1 Introduction

This note represents the impressions and opinions of the authors on the state of research, design, development and manufacture in the United States of rocket motors using nitric acid as oxidant. The mission, consisting of Mr. L.W. Broughton (R.A.E./R.P.D., Westcott), Dr. L.W.J. Newmann (Sir W.G. Armstrong Whitworth Aircraft Ltd.) and Mr. L.A. Wiseman (E.R.D.E., Waltham Abbey) visited some of the establishments concerned with the various aspects of such motors during the period April 26th - May 24th 1950. The necessary arrangements were made by the B.J.S.M. Washington, and the party was accompanied on many of the visits by Dr. L. Phillips of that organization.

The terms of reference of the mission included interchange of information with the American authorities up to United States security level of secret at the following establishments and firms:-

United States Defence Department, Pentagon, Washington D.C.
(28th April)

Headquarters of Materiel Command, United States Air Force, Wright Field, Dayton, Ohio, (3rd May)

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California (5th and 8th May)

Aerojet Engineering Corporation, Azusa, California (9th, 10th and 11th May)

Reaction Motors Incorporated, Dover, New Jersey (15th and 16th May)

The Naval Air Rocket Test Station, Dover, New Jersey (17th May)

The Applied Physics Laboratory, Johns Hopkins University, Silver Springs, Maryland, (19th May)

The M.W. Kellogg Company, Jersey City, New Jersey (22nd and 23rd May)

The contents of this note have been arranged from the functional aspect, and a separate index of agencies, establishments and firms is given in Appendix I so that reference can be made conveniently to the problems or products discussed with one particular research organization.

2 Propellants

2.1 General

In contrast to British opinion, the choice of propellants in the United States is, in general, governed by preference for self igniting combinations of fuels and oxidants, as it is not generally thought that non self-igniting propellants are inherently safer. As will be seen later, a critical review of the best propellants for use in the Services has not been made, and the problems of safety and storage of the weapon which are the responsibility of the vehicle designers, have in consequence received relatively less consideration by those concerned with rocket motor development than they have in the United Kingdom. An exception from the general policy is made of rocket assisted take off units for aircraft, in which white fuming nitric acid is used with JP.3 aviation fuel, as the latter is already carried in the aircraft for use

in the main engines. Consideration, however has been given to making these propellants self-igniting by means of additions to the oxidant.

Costs of the three main oxidizers (nitric acid, liquid oxygen and H.T.P.) are as follows: Nitric acid costs 3 cents/lb; liquid oxygen costs about 5 cents/lb, but the cost could be reduced to 2 to 3 cents/lb; H.T.P. could not be produced at less than 20 cents/lb by the electrolytic process, nor its price reduced below 15 to 20 cents/lb, even by production at the rate of 100,000 tons/year by the oxidation of propane.

The work being done on the various propellant combinations on which information was obtained is discussed in the following paragraphs.

2.2 White fuming nitric acid/JP.3

Since supplies of kerosine (JP.1) will be insufficient for aircraft use, a wide cut petroleum product including most of the gasoline and kerosine range, referred to as JP.3, is being developed for use in jet engines. As already stated, this fuel with white fuming nitric acid as oxidant is used in aircraft take off units. Variations in its composition have already aroused some anxiety in the Services, and have led to trouble in rocket motor combustion. If the variation in the aromatic content is considerable it is possible that the ignition properties may vary; the M.W. Kellogg Co. has found that rough burning occurs at combustion pressures below about 250 lb/sq in and gasoline has been found to have better combustion properties with white fuming nitric acid in these conditions.

Traces of water in JP.3 have been found to give trouble at low temperatures, owing to the separation of ice crystals. Also at these low temperatures wax crystals separate out from JP.3, and this property of the fuel determines the low temperature limit of the combination rather than the behaviour of the oxidant. The addition of 1-2% of ethyl acetate is effective in preventing ice formation, but once the wax has separated it does not readily go back into solution.

The same assisted take off unit using white fuming nitric acid and JP.3 is being developed by the Aerojet Engineering Corporation and by the Kellogg Co; this is described in Appendix II. The Bell Aircraft Co. is using an acid/gasoline propellant for the "Rascal" missile, but this firm was not visited. At present the Aerojet Corporation combustion chambers are being used, but eventually the firm will carry out the development of its own motor. Little work has been done on white fuming nitric acid/hydrocarbon systems by Reaction Motors Incorporated, but none by the Jet Propulsion Laboratory.

2.3 White fuming nitric acid/butyl mercaptan

The butyl mercaptans are a by-product of the oil refining industry. The ignition properties with white fuming nitric acid have been found to be very good, even at temperatures as low as -60°F. They give clean smokeless combustion with a specific impulse of 210 sec at a combustion chamber pressure of 300 lb/sq in. The usual fuel is represented by the empirical formula $C_{4.16}H_{9.78}S_{0.94}$ and has a molecular weight of 89.8¹.

The prospects for this fuel are viewed with a considerable amount of enthusiasm and supplies are stated to be adequate.

2.4 White fuming nitric acid/furfuryl alcohol

This propellant combination has been selected for a ramjet boost rocket being developed by the M.W. Kellogg Co. The prototype is to

produce a thrust of 90,000 lb for 4 seconds, but development is proceeding by stages i.e. from 3000 lb thrust to 15,000 lb and finally to 90,000 lb. The furfuryl alcohol fuel has given rough burning at combustion chamber pressures below 300 lb/sq in, but in this particular motor the pressure will be 700 lb/sq in.

The combustion chamber is uncooled, made of plain carbon steel, and has a specific length $L^* = 50$ inches. With this fuel the specific impulse obtained varies between 200 and 210 seconds. Below combustion chamber pressures of 300 lb/sq in a carbon steel venturi nozzle can be used, but at higher pressures it is essential to fit a ceramic insert such as Niafrax B (see para.3.1) on account of the increased rate of heat transfer.

2.5 Red fuming nitric acid/anhydrous hydrazine (N_2H_4)

These propellants are being used in a 2500 lb thrust motor under development by the Jet Propulsion Laboratory; the combustion chamber will have axial flow fuel cooling. Small experimental motors of 200 lb thrust have developed a measured specific impulse of 230 sec (theoretical value 246 sec) at a pressure of 300 lb/sq in in combustion chambers having specific lengths of 30 to 45 inches with these propellants. These performances were obtained with an injector system of the multiple impinging jet type in which each pair of oxidant jets inclined at right angles to each other impinged each at 45° with the axial fuel jet on an annular target plate². Two other types of burner system have not been as successful. When cooling with hydrazine it is essential to avoid stagnation points and to keep the temperature of the bulk liquid below $150^\circ C$.

The hydrazine is received as 97% hydrazine and the concentration may fall to 90% during storage. The toxicity effects on the staff handling this fuel are appreciable³. After exposure to hydrazine vapour, operatives sometimes develop sick headaches; a relatively larger proportion of women than men, however, appear to show sensitivity to hydrazine, and this is confirmed by some animal experiments in which after exposure of rats of both sexes to hydrazine vapour the female fatalities were 90% against 50% male fatalities in the same conditions. Dermatitis has been found to occur, in a mild form, but this soon clears up. In the three years that hydrazine has been handled by the Jet Propulsion Laboratory, in large quantities for the last eighteen months, there have been no cases of organic illness resulting from exposure to hydrazine liquid or vapour. The experience of the Aerojet Engineering Corporation has been equally satisfactory.

Some work has also been done by North American Aviation Inc. on lowering the freezing point of hydrazine. The addition of 10 - 15% of hydrogen sulphide was found to lower the freezing point to below $-30^\circ C$. The freezing point curve is very steep, however, on both sides of the eutectic point. A mixture of $83.56N_2H_4 + 12.50 HCN + 3.94 H_2O$ was found to have a freezing point between -35 and $-40^\circ C$ and a density of 1.068. The optimum specific impulse obtained from this mixture on combustion with liquid oxygen was 256 sec, compared with 262 sec from anhydrous hydrazine, at a combustion chamber pressure of 300 lb/sq in.

2.6 Red fuming nitric acid/liquid ammonia (NH_3)

This is regarded by the Jet Propulsion Laboratory as a very reliable propellant combination and no trouble in operating motors on these propellants has been experienced. Ignition is effected by a

Work going back to the old stand by

cartridge (about 1g) of lithium or calcium suitably located in the liquid ammonia feed system; this method has operated entirely without failure. It was agreed, however, by the Jet Propulsion Laboratory that this extreme reliability of operation was the only reason for using liquid ammonia. If other propellants proved equally reliable, there would be no reason for its use.

Diversion Solution

The use of ammonium nitrate/liquid ammonia instead of liquid ammonia has been considered by the M.W. Kellogg Co., as the former fuel has a lower vapour pressure and a higher density than liquid ammonia.

2.7 Liquid nitrogen tetroxide (N_2O_4)

Some experience of this oxidant with liquid ammonia and isopropyl alcohol has been acquired by the Jet Propulsion Laboratory and these propellants are said to have behaved very well in proof stand tests. It was learned that, if nitrogen tetroxide contains less than 0.1% water, it can be stored for at least two years in plain carbon steel containers.

2.8 Research programme on bi-propellants

It is understood that a programme for liquid propellant research for long range missiles has been laid down as listed below in ascending time scale:-

liquid oxygen/ethanol	-	system available
" /gasoline	-	under active development
" /ammonia	-)	
" /anhydrous	-)	under development
" /hydrazine	-)	
" /liquid hydrogen	-)	
liquid fluorine/liquid ammonia		
" /liquid hydrogen		

The development of boron compounds as fuels and of the oxidants, fluorine oxide (F_2O) and liquid ozone lies still further in the future.

2.9 Monopropellants

Nobody told them about CH40

Little work is being done on monopropellants. The Aerojet Engineering Corporation has ceased work on nitromethane on the test bed, but is continuing to do a little combustion work in the laboratory on this monopropellant.

As, however, the United States Navy is not wholeheartedly in favour of nitric acid, there is a possibility that the development of nitromethane as a monopropellant may be resumed. A final decision on this subject is to be made this year.

3 Materials

3.1 General

In general, the metallic materials used with nitric acid in the United States are the stainless steels and similar alloys. Relatively little work has been done on the corrosion resistance of these materials and the little that has been done is concerned more with corrosion resistance at high temperatures. The main reason for this is the present pre-occupation with cooling rather than long term storage problems. This in turn is probably due to the absence of long term storage requirements for

filled weapons from the specifications of the United States Services. In this connexion it is asserted at the Jet Propulsion Laboratory that the United States Army is prepared to transport propellants to the firing points, even overseas, and there fill the empty weapons, if this would lead to a more favourable solution of the guided missile problem.

Much work is being carried out on heat resistant materials for combustion chamber linings and venturi nozzles. Niafrax, a bonded silicon carbide material, seems to be the most promising material at the moment, but the employment of such materials leads to a heavy motor. No establishment has yet succeeded in reducing the weight of an uncooled motor to that of a regeneratively cooled motor of the same thrust. A discussion of the work done at the various establishments follows.

3.2 Metals resistant to nitric acid

3.21 Jet Propulsion Laboratory

As all the work done in this Laboratory has been concerned with red fuming nitric acid, only a few general comments could be given on the effects of white fuming nitric acid. The former is said to be less corrosive to aluminium alloys than the latter, presumably because any water that is formed reacts with the oxides of nitrogen to form nitric acid. On the other hand, stainless steel is said to be attacked less vigorously by white fuming nitric acid than by red fuming nitric acid. The effect of water concentration on the corrosion of stainless steel (types 303 and 347) and aluminium at 20°C by red fuming nitric acid has been examined, and it is found that the rate of corrosion of stainless steel is high if no water is present, but that it falls to a minimum with 2% water; aluminium, on the other hand, is most resistant when no water is present. There is reported to be some evidence that heat treatment in nitrogen improves the corrosion resistance of mild steel to red fuming nitric acid.

The Jet Propulsion Laboratory use the sand-casting aluminium alloy 356 T6 and the wrought aluminium alloys 61S and 62S for nozzles and valves. The stronger alloy 24S has also been used, but it is not as resistant to corrosion as the others.

Information on the behaviour of anhydrous nitric acid with aluminium is conflicting. The Jet Propulsion Laboratory has found that a white powder (perhaps $\text{Al}(\text{NO}_3)_3$) sometimes settles out on contact with aluminium. On the other hand, the opinion of the General Chemicals Co. is that storage in aluminium is satisfactory.

3.22 Aerojet Engineering Corporation

White fuming nitric acid is handled by this firm in stainless steel and it is found that the concentration of nitrous oxide rises above the specified limit of 0.5% in one to two weeks. There is also an appreciable attack on the metal so that the acid, after storage, may contain up to 5% inorganic salts in solution; this is unsatisfactory when the acid is used as the coolant.

The assisted take off unit (see Appendix II) under development by this firm has two acid tanks 6 ft long by 2 ft 6 in. diameter. In accordance with the U.S.A.F. specification, these tanks have to withstand storage conditions of 5 days at 160°F and 25 days above 80°F. These are regarded as exacting requirements and a considerable amount of work has been done on corrosion resistance mostly with respect to red fuming

nitric acid. The following categories of corrosion resistance for materials have been laid down by the Aerojet Engineering Corporation, the annual rate of loss of thickness being taken as the criterion.

- | | | |
|---|-------------------------------|-----------------------------|
| A | less than 0.0042 inches/year, | regarded as fully resistant |
| B | 0.0042 to 0.042 | " " satisfactory |
| C | 0.042 to 0.12 | " |
| D | 0.12 to 0.42 | " |
| E | greater than 0.42 | " |

The results of tests on a number of materials (mostly stainless steels) are given in the following table:

Corrosion of metals by nitric acid				
Acid	Material	Temp. °F	Result	Comments
8% R.F.N.A.	2 S.O. annealed (99.5% aluminium)	160	B	-
16% R.F.N.A.	2 S. half-hard	160	D	-
6.5% R.F.N.A.	61 S.T6	160	A	This welds satisfactorily and welds can be heat treated; T.S. 55,000 lb/sq in. Y.P. 40,000 to 45,000 lb/sq in.
"	"	200	B	
"	61 S.T6 annealed	160	B	T.S. 25,000 lb/sq in
"	L.605 (Stellite No.5)	80	A	-
"	"	160	A	
"	"	350	B	
16.5% R.F.N.A.	Hastelloy A	80	E	-
"	" B	80	D	
"	" C	80	A	
"	" D	80	E	

19/9 stainless steel, with 0.2 to 0.5% titanium was strong at high temperatures, but showed no more than fair corrosion resistance. It welded well, but there was some grain growth of the parent metal near the weld. Corrosion tests of tanks? diameter by 2 ft long, constructed of various materials, which were half filled with white fuming nitric acid and maintained at 160°F(?) have also been carried out. The results were recorded by weighing them every five days, and are shown graphically in Fig.1. Most of the material was lost from the upper end of the tank where the residual thickness of metal was 0.010 in. for 19.9 DL steel and 0.013 in. for the type 347 steel.

Some attention has been given to surface treatment. A sample of 41/30 chrome steel was sprayed with a thickness of 0.030 in. of aluminium and then partially immersed in white fuming nitric acid at 160°F for 5 days. The aluminium was completely removed from the portion

immersed in the acid, but, apparently, that above the surface was not attacked. Another possible method of surface protection for mild steel is considered to be gas plating by thermal decomposition of metal carbonyls.

3.3 Non-metallic materials resistant to nitric acid

Undoubtedly the most satisfactory plastic material is Kel F, (polymonochlorotetrafluorethylene). This is manufactured by the M.W. Kellogg Co., but the processing is carried out by other firms. Thin sheets, for example, are made by the Visking Corporation, Chicago, from tubes continuously extruded and expanded by air. The method produces sheets of uniform thickness from 0.001 in to 0.01 in and up to 72 in wide⁴. The trade name is "Trithene"; type A is unplasticized, and type B is plasticized with a lower polymer of Kel F. The sheets have excellent strength properties, with high flexibility and almost total freedom from pin holes. At temperatures above 375 - 390°F the film tends to return to its original dimensions. It can be welded to form joints and seams by a high frequency heating process, with a weld strength as high or higher than that of the original material; the Electronic Process Co., San José, Cal. has done work on this problem. Thermal welding is unsatisfactory as the plasticizer is removed from the material near the weld and thus the tear-strength is reduced.

The unplasticized moulding powder costs about \$ 14.75/lb in 100 lb lots, the plasticized material approximately \$ 15.75/lb, whereas the processed film costs about twice as much i.e. \$ 30/lb. About 80 to 90 sq ft of 0.001 in thick film can be obtained from 1 lb of material.

The same material can also be applied to metal surfaces by spraying or dipping. The coat is baked at 450 - 500°F for about 20 minutes, and successive coats, each about 0.00125 in thick, can be built up to a total thickness of 0.06 in by this method. Aluminium, tin, steel and stainless steel have been coated in this manner, but since copper forms a loose oxide, a coherent film of Kel F has not been formed on this metal. The films are stated by the Kellogg Co. to be free from pin holes, but no storage tests with nitric acid in coated containers have been carried out.

This material has also been used by the Aerojet Engineering Corporation, but it is clear that the latest information from the Kellogg Co. has not been obtained. The Aerojet Engineering Corporation have had no success in the construction of flexible bags, but find it satisfactory for gaskets and pump seals. Complaint is made, however, that sealing rings of hollow circular section in this material are unsatisfactory at low temperature, owing, however, to lack of flexibility and not to lack of resistance to chemical attack. Vinylite is generally used by the Aerojet Engineering Corporation for O-section rings in contact with acids.

Teflon (polytetrafluorethylene) though only half as expensive as Kel F, appears to be less satisfactory and the production of flexible bags from this material seems to be unlikely. It has been considered, by both the Aerojet Engineering Corporation and the Jet Propulsion Laboratory, however, for the protection of mild steel by spray coating. Pieces of mild steel spray coated with six layers of Teflon were seen at Wright Field. These had been in contact with nitric acid for 24 hours at 160°F and displayed blisters between the film and the metal. These blisters contained acid, and thus, although some degree of protection was afforded, this was by no means complete.

3.4 Heat resistant materials

3.4.1 United States Air Force, Wright Field

Active research and development of heat resistant ceramic materials is being pursued by United States Air Force at Wright Field. The most promising materials appear to be those based on silicon carbide and this refractory has been tested with red fuming nitric acid/aniline, red fuming nitric acid/gasoline and xylidine, and white fuming nitric acid/JP.3. The most satisfactory form of silicon carbide is "Niafrax" made by the Carborundum Co., and this appears to be the best material for combustion chamber linings, and probably also for nozzles. Silicon carbide has a high thermal conductivity and it is, therefore, necessary to insulate the lining from the chamber wall. Ciment Fondu has been used as a cement for this purpose and experiments are being carried out to improve its insulating properties further by the addition of a foaming agent. The United States Air Force, Wright Field, uses a vibration technique to introduce the cement without air-bubbles whereas at the Battelle Memorial Institute the cement is pumped in. The objection to air-bubbles is that the liner is unsupported at the point where the bubble is situated. The cement expands and this compresses the liner and seals any cracks. The thickness of the cement layers is between $\frac{1}{8}$ and $\frac{1}{4}$ in but this is not critical. Plaster of Paris has also been used as a cement, but this is only effective for one firing since it breaks up with repeated use. Information on the assembly of these ceramic liners is being supplied to the British Joint Services Mission.

One silicon carbide lining and venturi has been found to have a life of about five runs of one to two minutes duration in a 1000 lb thrust motor using red fuming nitric acid/gasoline or xylidine; an even longer life has been obtained for a liner of similar design in a 400 lb thrust motor. The longest continuous run so far obtained with a liner of this material is 188 sec with red fuming nitric acid/aniline, but this resulted in slight erosion of the venturi nozzle. In these conditions, at the end of a 2-minute run the temperature of the steel outer shell reaches about 1000°F.

A resin bonded mixture of zirconia and silicon carbide, which need not be fired before the liner is used, has also given promising results. This material is subject to attack by nitric acid before firing, but after firing the resistance is good. These liners are also fairly resistant to erosion, but nozzles of the same material are usually eroded severely after a burning time of 1 minute.

A mixture of graphite and silicon carbide is easier to form than silicon carbide alone; it seems to make better linings, and since it remains somewhat plastic any cracks formed in the liner close up. Venturi nozzles of this material become roughened rather than erode, and it is considered that their resistance to roughening can be improved by better manufacturing technique. A hard impregnated graphite, known as Graphitar 15, has been found satisfactory for venturi nozzles. Zirconium boride has been tested in small nozzles by the United States Bureau of Ordnance, but the detailed results were not known at Wright Field.

The present designs of combustion chambers with refractory linings appear to be about 50% heavier than the corresponding combustion chambers with regenerative cooling. In order to reduce this weight, work is being carried out to make combustion chambers by spraying metal on to ceramic liners. Nevertheless, it is considered at Wright Field that, for meeting missile requirements where weight is not a primary consideration, the

simple refractory-lined combustion chamber shows advantages over the regeneratively cooled type.

3.42 Jet Propulsion Laboratory

At this establishment experiments are being made with refractory linings consisting of zirconia (200 mesh), silica or silicon carbide mixed with water glass. These are not fired before use. The method of applying the lining to the combustion chamber is shown in Fig. 2a. The former and the plastic liner are provided with holes for the escape of moisture. After filling, the mix is dried at 100°C and then the former and the plastic liner are removed; the chamber is then ready for firing. During the firing some spalling occurs at the venturi throat, but material from the chamber lining is redeposited there; this indicates that the heat transfer through the combustion chamber wall increases, but that at the throat decreases.

Silicon carbide is found to be the best of the materials tested, but silica and zirconia appear to be almost as good; silica, incidentally, is very viscous above the melting point and flows out of the motor on to the venturi nozzle during the firing. In all the tests red fuming nitric acid has been used for the oxidant and aniline, hydrazine or liquid ammonia for the fuel.

3.43 Aerojet Engineering Corporation

The contract held by the Aerojet Engineering Corporation for the development of the R.A.T.O. unit to operate on white fuming nitric acid and JP.3 or gasoline described in Appendix II restricts the firm to the development of "Niafrax" linings and venturi nozzles. The exact composition of this material is not known to the firm; this material is found not satisfactory in oxidizing conditions and it dissociates at about 4000°F. However, in motors of 5000 lb thrust using red fuming nitric acid/aniline good results have been obtained, and the preliminary results with white fuming nitric acid/gasoline in the same motors are satisfactory. The thermal conductivity of "Niafrax" is slightly less than that of stainless steel, and the density of "Niafrax A" is 2.85. To reduce the weight, however, experiments are to be undertaken with a porous "Niafrax" of density 2.15, and it is considered that the latter material will also be suitable for venturi nozzles.

The "Niafrax A" liner is made separately from the venturi and secured to the combustion chamber wall with Aluminite cement. It is very difficult to make liners less than $\frac{3}{8}$ in thick, and an additional $\frac{1}{8}$ in is needed for the cement layer; cement bonding is quite satisfactory except for resistance to acid. For motors required for repeated operation a silicate cement will probably be used. The bonding is carried out by positioning the liner centrally in the chamber and adding the cement from one side only, but an equal distribution of cement is ensured by the use of a vibrating table to facilitate the flow.

The venturi is made separately from the liner, and until recently it has consisted of a ring of "Niafrax" of the same external diameter as the chamber liner, as shown in Fig. 2b. The weight of this piece is 19 $\frac{3}{4}$ to 20 lb for a 5000 lb thrust motor. Experiments, however, are being made with venturi nozzles of the shapes shown in Fig. 2c and 2d, which are considerably lighter, but have less heat capacity; so far, endurance of 15 sec have been obtained with white fuming nitric acid/gasoline. Normally, plain butt joints are used between liner and venturi with a cement thickness of 0.010 to 0.015 in; it may, however, be necessary

to use a spigoted joint when the main combustion zone is in the neighbourhood of the joint. No form of gasket is used between the rear face of the liner and the injector, but it is desirable to arrange that the face of the injector protrudes a little forward of the joint face.

"Niafrax" lined motors can undergo a reasonable extent of rough handling, such as being dropped from 4 to 5 feet. Cracks are formed in the lining, but the pieces do not drop out and the cracks are no disadvantage to the operation of the motor. These motors have also withstood vibration tests carried out at Wright Field for simulating aircraft conditions.

Graphite liners have not proved successful with hydrogen peroxide, though they have been fairly satisfactory with nitromethane. Graphitar 15 (S.G.1.7) has been used successfully at Wright Field; although this material is soft it has proved suitable in the nozzle.

The Aerojet Engineering Corporation also intends to carry out experiments with ceramic coatings on stainless steels. Work has been done at the Universities of Illinois and Ohio on the development of ceramic coatings for gas turbine combustion chambers. A number of good coatings which work well at 1600°F and a pressure of 50 - 75 lb/sq in have been developed at Ohio University, whereas the University of Illinois has worked mainly on ceremals (metal ceramics). The Aerojet Engineering Corporation has been able to extend the life of an uncooled chamber working on white fuming nitric acid/JP.3 from 6 to 8 seconds by the use of a ceremite coating in the chamber though the coating spalls off suddenly after 8 seconds.

The Aerojet Engineering Corporation confirms that the advantage of uncooled motors is their simplicity and the disadvantage is their weight. For a 5000 lb thrust unit, the motor should not weigh more than 45 lb, whereas the present motors lined with Niafrax weigh 60 to 63 lb; this includes the injector but not the valves. By welding the injector to the combustion chamber, a saving of about 10 lb is anticipated, but the firm expects to be able to make a liquid cooled motor weighing 30 lb for 5000 lb thrust.

4. Injectors

4.1 General

Most of the injectors seen were of the impinging jet type, and the general opinion is that this type gives as good if not better results than any other. This applies to both hypergolic and non-hypergolic propellants. On the question of target plates with impinging jet injectors, opinion appears to be more divided as some establishments use them and others do not, but evidence seems to show that the target plate gives a higher rate of heat transfer, but is rather inclined to burn away.

Of other types of injectors only two were seen (a) a "shower head" injector at the Aerojet Engineering Corporation and (b) a "mushroom" injector at Reaction Motors Incorporated. The former is interesting as it consists of a large number of oxidant and fuel jets drilled alternately over the head of the injector through which the fuel and oxidants are injected axially down the chamber. Although its performance is slightly inferior to that of an impinging jet type, it has a lower rate of heat transfer and should be an easier type to manufacture. Furthermore it is found to give more stable combustion particularly in large motors. The second injector (b) consists of two concentric ring slits in the centre of the injector head, one each for oxidant and fuel. The width

of the slits can be varied between zero and the maximum values and thus enables the flow of propellants to be shut off at the injector. Although this eliminates propellant valves in the rest of the system, it makes the injector complicated; this is still under development.

A comprehensive series of tests has just been completed by the Aerojet Engineering Corporation to determine the effect of various parameters on the performance and heat transfer of an impinging jet type injector. Unfortunately from our point of view the propellants used were hypergolic (nitric acid/aniline), and although it is a most useful piece of work it is not known to what extent the results can be applied to non-hypergols.

4.2 Jet Propulsion Laboratory

This firm has done no injector work on nitric acid and hydrocarbon (such as kerosine) fuels. All of their work has been on self igniting fuels.

4.21 Target plate injectors

The Enzian² type of burner and target plate has been used quite successfully. The target plate, which is made of stainless steel, is integral with the head and relatively thick ($\frac{3}{16}$ in), whereas the jets are made to impinge on the plate and close to its edge. The arrangement gives a higher rate of heat transfer than plain impinging jets, but gives a higher performance when using either ammonia or anhydrous hydrazine as a fuel.

Details of an injector for a 2500 lb thrust motor are as follows:-

Propellants	- red fuming nitric acid/anhydrous hydrazine
Propellant flow	- 12 lb/sec
Target plate	- stainless steel, $\frac{3}{16}$ in thick and integral with the head
16 pairs of oxidant/fuel jets on a pitch circle diameter of about 3 in	
Diameter of chamber - 6 in	

4.22 Injector for Corporal E

This motor has a thrust of 20,000 lb and uses red fuming nitric acid with an alcohol/aniline mixture as the fuel. The injector is of the impinging jet type without target plate and there is one oxidant to one fuel jet. The angle between the jets is 40° , each jet stream is about $1\frac{3}{4}$ in long and the streams impinge on a pitch circle of about 7 in diameter within an 11 in diameter combustion chamber. The oxidant jet is nearer to the wall of the combustion chamber and is so arranged that, if it fails to impinge on the corresponding fuel jet (e.g. in the event of obstruction of the fuel jet), it passes out through the venturi without touching the walls.

This injector gives 89% of the theoretical thrust but it is expected that 93% should be obtained regularly, a figure which has been recorded on occasional firings.

4.23 Pre-mixing injectors

Some work is being done on mixing nozzles for nitric acid and aniline. So far only small scale firing tests have been made with a

50 lb thrust motor, but a mixing nozzle for a 1000 lb thrust motor, although made, has not yet been tested.

The mixing nozzle is quite simple and consists of a cylindrical tube open at one end and closed at the other except for two holes drilled tangentially into the cylinder for feeding the oxidant and fuel. The propellants mix in the cylinder and are then discharged from the open end into the combustion chamber. The mixing nozzle for 50 lb thrust has a length of $\frac{1}{2}$ in and a bore of $\frac{1}{10}$ in; the pressure drop across the nozzle is 200 lb/sq in and the time of stay in the nozzle is 2 milliseconds. For the initial tests a small quantity of water was fed through the fuel orifice, when starting the motor, to ensure that the acid arrived first, but this is now found to be unnecessary. The combustion chamber has a diameter of 2 in. and a length of 4 in. The following figures show the comparative performance of the mixing nozzle and impinging jet injector:-

	<u>L* in</u>	<u>Relative efficiency</u>
Impinging jet	100	100%
(Below this value of L* the efficiency falls off)		
Mixing nozzle	50	100%
" "	30	90%

The larger mixing nozzle for 1000 lb thrust has a length and diameter of about 2 in and $\frac{1}{2}$ in respectively, and a time of stay of 4 milliseconds. Tests on this nozzle should be started soon.

4.3 Aerojet Engineering Corporation

Most of the work on nitric acid has been done with hypergolic fuels, but some investigations are now being carried out with gasoline or JP.3 mainly in order to develop an injector for an A.T.O. unit for the B.47 aircraft. (See Appendix II for details of this motor.)

4.31 "Shower head" injector for A.T.O. motor

This injector is being developed for use in the A.T.O. motor for the B.47 aircraft. This motor has four combustion chambers each giving a thrust of 5000 lb, and uses either gasoline or JP.3. The injector is of the multi-hole type, that is, a large number of oxidant and fuel holes are drilled in alternating lines across the injector face, injection being directed axially down the combustion chamber (see Fig.3). The value $C^* = 4600$ ft/sec for the effective exhaust velocity obtained with this injector in a chamber with $L^* = 45$ in is 85% of the theoretical figure; this is slightly less than that given by the comparable impinging jet injector, but the rate of heat transfer, which is from 0.74 to 0.9 B.Th.U/sq in/sec, is rather lower. On recent tests 'scoring' has occurred in the combustion chamber throat; this has been attributed to impingement by some of the acid jets. The injector is, therefore, being modified by arranging an outer circumferential ring of fuel jets to give a film of fuel between the acid jets and the wall of the chamber.

4.32 Injection parameters for hypergolic propellants

An experimental investigation of various injection parameters with respect to performance and heat transfer has been carried out by the Aerojet Engineering Corporation with red fuming nitric acid/aniline in a motor with the following characteristics:-

Combustion chamber diameter	4.25 in
L*	43 in
Area ratio	6/1
Combustion chamber pressure	315 lb/sq in
Thrust (maintained constant by injecting more propellants as necessary)	1000 lb

The injector selected for testing was a 1:1 impinging jet injector (Fig.4a) with the oxidant jets arranged nearer to the combustion chamber walls. This location of the oxidant jets is preferable as the heat transfer is then lower than that produced by locating the fuel jets on the outside and the oxidant jets nearer to the combustion chamber axis. Both series of jets, however, are arranged normal to the surfaces of the chamber in which the nozzles are fitted.

Preliminary investigations were made on two other types of injector. One was of the 'Enzian' type², but this frequently burned out; the other was a 2:1 impinging jet type (i.e. two oxidant jets and one fuel jet, Fig.4b) which, however, gave rise to starting problems. As already stated the propellants were red fuming nitric acid and aniline; similar work on non-hypergolic propellants has not yet been carried out.

The parameters (see Fig. 5a) were chosen for the experiments:-

- z = perpendicular distance from point of impingement of jets to injector face
- γ = angle between oxidant and fuel jets
- β = angle between resultant of the two jets and the combustion chamber axis, reckoned positive towards the combustion chamber wall, and negative towards the centre line of the chamber
- Y = distance between point of impingement and chamber wall

These parameters are applicable, of course, to 1:1 impinging jet injectors only. The results obtained are discussed in the following paragraphs.

Effect of γ

In Fig.5b is plotted the rate of heat transfer q against γ and in Fig.5c, the effective exhaust velocity C^* against γ , for the specific case where $Y = 0.9$ in. and β is equal to some unknown but constant angle; the curves may be regarded as typical, but they merely show the trends in the values of q and C^* in these conditions. q increases rapidly as γ becomes less than 45° and it is concluded that $\gamma \approx 60^\circ$ is about the optimum angle since the value of q at $\gamma \approx 45^\circ$ is some 70% greater than that at 60° whereas there is not a corresponding decrease in performance, as indicated by the rather slow drop in the value of C^* .

Effect of β

Fig.5d and 5e show the graphs of q and of C^* respectively against β for the specific values $\gamma = 45^\circ$ and $Y = 0.9$ in. It will be seen from Fig.5d that the heat transfer q in the venturi nozzle starts to rise rapidly when β is about 10° ; when $\beta = 0^\circ$, q is rather more than 2 B.Th.U/sq in/sec, but C^* is tending to approach its maximum value. It is, therefore, considered that the best value of β is to be found between 0° and 10° .

Effect of Y

The variation in q for values of $Y = 0.5, 0.7, 0.9, 1.1, 1.3$ and 1.5 inches is shown for two values of β , -0° and 10° and for $\gamma = 45^\circ$ in Fig. 5f. The overall value of q is nearly constant and there was no change in C^* , but the heat transfer in the nozzle passes through a minimum as β varies from 0° to 10° at $Y \approx 0.7$ to 0.9 inches; this gives the best value of Y .

Effect of z

Fig. 6a and 6b show the graphs of q and C^* respectively against z . For maximum performance it can be seen that the impingement should be very close to the injector, but for ease of construction and in view of the slight decrease in heat transfer the optimum value is taken as 0.1875 inches.

Effect of propellant velocity

The effect of the propellant velocity was examined by the use of replaceable injector plates (see Fig. 6c). Four different plates were used, with 16, 12, 9 and 6 pairs of holes respectively. After testing them, the holes were redrilled so that the kinetic energy ratio of fuel to oxidant was the same i.e.

$$(V^2/2g)_{\text{fuel}} = k(V^2/2g)_{\text{oxidant}}$$

Four points were selected for each of the following ratios:

$$(V^2/2g)_{\text{fuel}} = 1.5(V^2/2g)_{\text{oxidant}}$$

(this corresponds to equal pressure drops through the injector nozzles for oxidant and fuel)

$$(V^2/2g)_{\text{fuel}} = (V^2/2g)_{\text{oxidant}}$$

$$1.5(V^2/2g)_{\text{fuel}} = (V^2/2g)_{\text{oxidant}}$$

$$2(V^2/2g)_{\text{fuel}} = (V^2/2g)_{\text{oxidant}}$$

A graph of the exhaust velocity against kinetic energy of the fuel is shown in Fig. 6d; the optimum kinetic energy ratio is considered to be $E_{\text{fuel}}/E_{\text{oxidant}} = 1/1.5$, and the evidence seems to suggest that the ratios of the pressure drops are more important than their absolute values in maintaining steady combustion. Thus in the "Shrike" motor, chugging (see para. 4.43) occurs with $\Delta p_{\text{oxidant}} = 70$ lb/sq in and $\Delta p_{\text{fuel}} = 45$ lb/sq in, where Δp is the pressure drop through the injector system, whereas in this experimental motor stable combustion is obtained with $\Delta p = 35$ lb/sq in for both oxidant and fuel.

Effect of absolute stream size

This effect was examined for the conditions of $\gamma = 60^\circ$, $\beta = 0^\circ$ and $(V^2/2g)_{\text{fuel}} = 1.5(V^2/2g)_{\text{oxidant}}$ i.e. $\Delta p_{\text{fuel}} = \Delta p_{\text{oxidant}}$. The procedure was to provide injector plates with 20, 16 and 12 pairs of jets. After firing, alternate pairs of jets were plugged, and the remainder drilled out to secure the same pressure drop through the injector. In this way, the motor was run with injectors having 20, 16, 12, 10, 8, 6, 5, 4 and 3 pairs of jets, of gradually increasing diameter. Fig. 6e and 6f show the trend of thrust and heat transfer against d_f , the diameter of the fuel orifice. The results obviously favour a large number of pairs of jets of small diameter for efficient combustion and minimum heat transfer. In no case was there any ignition difficulty.

Effect of misalignment

When a pair of jets impinges perfectly the misalignment is said to be zero. 100% misalignment is obtained when one jet is tangential to the other at the point of intersection. In the experimental motor 100% misalignment occurred when the axis of the acid orifice and effectively the jet was displaced 4° to the axis of the fuel orifice. The effect was examined by using an injector plate with 12 pairs of jets and tests were made at displacements of 0, 1, 2, 3 and 4° i.e. with 0, 25, 50, 75 and 100% misalignment. The resulting catastrophic decrease of thrust is shown in Fig. 6g. With 75% misalignment there was much smoke and hardly any flame; with 100% misalignment the through-put was 9-10 lb/sec of propellants, the chamber pressure was 2 lb/sq in, the thrust had fallen to nil, and the propellants burned outside the motor: there was, however, some exothermic reaction within it.

Optimum values

The optimum values of parameters and conditions for this motor working on red fuming nitric acid and aniline, can, therefore, be summarized as:-

- $z \approx 3/16$ in
- $\gamma \approx 60^\circ$
- $\beta \approx 0^\circ$ to 10°
- $Y \approx 0.7$ to 0.9 in
- Equal pressure drop for oxidant and fuel through the injector
- As many pairs of jets as possible
- 0% misalignment

4.4 Reaction Motors Inc.

The majority of the experience of nitric acid obtained by this firm has been with hypergolic fuels, but some work on aviation fuel JP.3 is now being done. No work has been done with JP.1 (kerosine). Satisfactory combustion of white fuming nitric acid and JP.3 has been obtained at chamber pressures down to about 150 lb/sq in.

4.4.1 'Lark' injector

This injector, shown in Fig. 7, was developed for the 'Lark' missile which uses white fuming nitric acid and aniline; it gives about 96% of the theoretical performance. Two acid jets to one fuel jet are used in order to make the jet diameters more nearly equal, and the fuel jet is located nearest to the combustion chamber wall in order to provide a film of fuel between the acid and wall.

This type of injector has been used successfully with white fuming nitric acid and JP.3. The firm does not know how it can be enlarged satisfactorily and considers it would be preferable to use a number of these injectors for bigger motors. This has been done successfully in liquid oxygen/alcohol motors. One advantage is that if the back plate of the injector becomes distorted, these small injectors are less likely to be affected than one large one.

4.42 "Mushroom" type injector

Reaction Motors Inc. is also developing another type of injector in which the propellants are fed into the chamber through two concentric ring slits in the centre of the injector head. The acid is fed through the centre with a swirling motion and impinges on a mushroom shaped head which deflects it towards the walls. Immediately it leaves the mushroom head it meets the fuel spray. The combined jet then impinges on a curved target plate which deflects it down the chamber. The width of the oxidant slit is 0.040 - 0.045 in. and that of the fuel slit is 0.020 in.

The principal advantage of this injector is that the mushroom head controlling the width of the acid slit and the sleeve controlling the width of the fuel slit can be moved axially to control the width of slit and also to act as shut off valves. Movement of the valves is effected hydraulically by annular pistons; the pressure of the acid or fuel on the back of its respective piston keeps the valve closed when the chamber is not firing. This injector is not working satisfactorily and development is still continuing.

4.43 "Chugging"

"Chugging" is a term used to describe a low frequency combustion vibration, a phenomenon which is occasionally experienced. To attempt to prevent it a minimum pressure drop across the injectors of at least 75 lb/sq in, and preferably of 100 lb/sq in, is used. It has also been found that, with a given motor, the injection pressure at which "chugging" occurs depends upon whether the motor is starting or ceasing to "chug". That is, if "chugging" occurs at a certain injection pressure (say P_1) when lowering the injection pressure then to suppress it the pressure has to be raised to a pressure which is higher than P_1 .

4.5 Naval Air Rocket Test Station

This station has only recently been established and so far very little practical work has been done. Some of the staff at this station, however, have had considerable experience at other organizations and the opportunity was taken to discuss injector problems with them, and in particular with Mr. Abramson who until recently was with the Bell Aircraft Co. It should be borne in mind however, that most of his experience has been obtained with liquid oxygen motors. He made the following points:-

(a) The impinging jet injector continues to be the most satisfactory type, and with careful design and manufacture it should be possible to obtain efficiencies up to 95% of the theoretical value. When this type is made on a production basis, however, it will be difficult to obtain efficiencies much better than 90%.

(b) The jets should be of small diameter to give uniform distribution of the fuel and oxidant inside the combustion chamber.

(c) The jet stream diameter should be the same for both oxidant and fuel.

(d) The jet holes must be very cleanly finished and all tool marks eliminated. The holes must be drilled in the direction of flow in order to obtain a clean outlet hole. Any suspicion of a burr must be avoided.

(e) The upstream entrance to the jet hole must be provided with a small chamfer to prevent cavitation. If cavitation takes place a discontinuity will occur in the corresponding flow/pressure curve.

(f) The length/diameter ratio of the jet holes should be about 3/1, but certainly not less than 1/1.

(g) The jets should impinge close to the injector face, although this may mean pitting of the injector face under conditions of repeated operation of the motor.

(h) The downstream face of the jet hole should not be recessed as this sometimes causes a backwash of the combustion gases leading to burning of the injector face.

(i) The angle of impingement of the jet streams should be about 75°. (This refers particularly to liquid oxygen motors.)

4.6 M.W. Kellogg Co.

The majority of the work done by this firm on injectors using nitric acid and aviation fuel JP.3 is associated with their contract for the development of a motor to power an A.T.O. unit for B.47 aircraft. The details of this motor are described in Appendix II.

4.61 Injector for A.T.O. motor

This injector is fitted to a motor intended to develop 5000 lb thrust and is of the impinging jet type with target plates; the injector is shown in Fig.8. It consists of two annular rows of fuel jets and two annular rows of oxidant jets; one pair of jets is directed towards the combustion chamber wall so as to impinge on a target plate parallel with it, and the alternate pair is directed inwards so as to impinge on a target plate in the centre of the chamber. To cut off the propellants instantaneously and thus to prevent them dribbling into the chamber, a shut-off valve is arranged behind each jet; these valves are held on to their faces by the application of hydraulic pressure to a small piston integral with each valve. The injector gives 95% of the theoretical performance at a combustion chamber pressure of 400 lb/sq in with a specific impulse of 220 lb sec/lb, and 90% of the theoretical figure at 300 lb/sq in. Below 200 lb/sq in or so, combustion begins to get rough. The heat transfer to the chamber is about 70% of the calculated value; the reduction is attributed to the cooling effect of the jet stream on the walls of the chamber.

Various modifications such as shortening the paths for the jet streams, varying the angles between them, and varying the pitch circle diameter of the jets have been made to this injector. None of these modifications, however, were very successful as they gave rise either to burning of the face of the central target plate, or burning on the parallel target plate or burning on the face of the burner between the inner and outer rows of jets. An account of all this work has been written and it is hoped to obtain a copy of the report.

The development of this injector began by the preliminary construction of an Enzian target plate type injector to give a thrust of 500 lb.

No trouble was experienced due to burning of the target plate, but explosions occurred between the target plate and the injector head and resulted in the destruction of the target plate. This defect was overcome successfully by locating the target plate close to and parallel with the chamber wall.

Some comparative tests of the effect of the target plate on the impinging jet injector were made at 500 lb thrust using nitric acid and anhydrous hydrazine with the following result

Chamber pressure	300 lb/sq in,	with target plate,	specific impulse	210 lb sec/lb
"	"	"	without target plate,	specific impulse 190 lb sec/lb

This confirms the experience obtained with hydrazine with these types of injectors by Jet Propulsion Laboratory.

5 Ignition

5.1 General

As already mentioned in para. 2.1, the use of hypergolic propellants is favoured in the U.S.A. Some information on the ignition properties of this type of propellant was obtained; apparently the main problem is to reduce the ignition delay at low temperatures to an acceptable figure. The good ignition properties of the butyl mercaptans, therefore, furnish the main reason for the enthusiasm shown for these fuels.

Some work on the measurement of ignition delay in rocket motors has been started at the Jet Propulsion Laboratory. The delay is measured by allowing the jets to impinge at the end of a probe which completes a circuit between the probe and the nitric acid jet. The time elapsing between the completion of this circuit and the achievement of peak pressure in the combustion chamber is taken as the ignition delay. With red fuming nitric acid/furfuryl alcohol the figures obtained by this method agree with laboratory measurements.

The main interest of the visit however, was the work being carried out on the ignition of white fuming nitric acid/aviation fuel JP.3 and gasoline. As a hypergolic propellant combination formed by the addition of suitable substances to white fuming nitric acid would be accepted by the United States Services, some consideration to this problem has been given by the Jet Propulsion Laboratory. The method of approach is to find additives to nitric acid which will reduce the ignition delay with a hypergolic fuel. Thus the delay with red fuming nitric acid/aniline can be reduced from about 36 milliseconds to 4 milliseconds by the addition of 1-2% of ammonium metavanadate to the acid.

5.2 Aerojet Engineering Corporation

The ignition of motors using white fuming nitric acid/aviation fuel JP.3 is also a major problem at Aerojets, particularly at low temperatures. The following methods have been tried:-

(a) The use of additives to the acid to make the propellants self-igniting. No success has been obtained apart from one compound - probably some oxide of manganese (Mn_2O_7), and no further successful development is anticipated.

(b) Electric heating of the combustion chamber wall. This involves an excessive consumption of power, as a minimum temperature of 800 - 1000°F has to be attained.

(c) Spark ignition. Little success has been obtained with this method.

(d) Glow plugs. Most of the work is concentrated on this method. Hitherto standard Diesel engine igniter plugs have been used; these are 1 to $1\frac{1}{2}$ in. long by $\frac{3}{8}$ in. diameter wound with No.16 or No.14 Ni/Cr wire containing 80% nickel and 20% chromium. A standard of at least 100 ignitions from the same plug with satisfactory operation at low temperatures has been set. Attempts to secure the ignition of sufficient propellant to start a 5000 lb thrust motor at temperatures down to -37°F were unsuccessful, and ignition is now carried out by means of a series of combustion chambers. Thus, a glow plug is used to ignite propellants giving an equivalent thrust of 3 lb in a primer chamber; the combustion gases from this ignite the propellants in a starter chamber of 50 lb equivalent thrust, and the gases from the latter furnish the source of ignition for the main motor of 5000 lb thrust.

The initial design of primer chamber is shown in Fig.9a; it is provided with one oxidant jet and one fuel jet arranged to strike the igniter plug at about the third coil of the heater wire. With this arrangement the life of the igniter plugs was short, and modifications such as that shown in Fig.9b were tried, but this tended to produce explosions when the propellant temperature was 0°F or less, particularly when the chamber was colder. Spray nozzles, therefore, were used in the primer chamber and this alteration resulted in better ignition and longer life of the igniter plug. Combustion at low pressures and temperatures, however, was still unsatisfactory. This was remedied by providing the primer chamber with a choke to raise the specific length L^* of the primer chamber to 120 in. The present ignition arrangement is shown diagrammatically in Fig.9c and this assembly has functioned satisfactorily with propellants, valves, pipe lines, primer chamber and starter chamber at -50°F. The pressure drop at the fuel and oxidant orifices in the primer is about 10 lb/sq in: one pair of orifices is used. The starter chamber is provided with three pairs of impinging jet orifices - see Fig.9d. The primer and starter chambers are uncooled. To ensure reliable starting the correct timing sequence is obtained by means of hydraulic delays in the propellant feed lines. There is one main valve which controls the flow to primer, starter and main motor, and a second valve for controlling the flow to the starter and primer. The time record of a typical start is shown in Fig.9c; in this record zero time is the instant when the starting switch is closed.

The flow of propellant to the primer and starter chambers is cut off when the main chamber fires. It is also arranged to be cut off after a preset time if the main chamber has not fired, or if the required working pressure is not obtained.

There is now a tendency to replace the impinging jet nozzles in the starter chamber by swirl nozzles as these give more reliable starting. Gasoline is found to ignite more readily than aviation fuel JP.3.

5.3 Reaction Motors Incorporated

This firm has no contract for the development of acid/aviation fuel motors, so very little work has been done on this combination of propellants. The majority of their investigations of the ignition of acid

oxidants has been made on self-igniting fuels based on red fuming nitric acid or on liquid oxygen/alcohol. With the latter combination squib igniters, which had undergone a considerable amount of development, were used. In the small amount of development devoted to the electrical ignition of acid/gasoline propellants endeavours have been directed to minimizing the energy requirements for ignition, and 72 watts is quoted as a maximum figure; efforts have also been made to reduce the time required for ignition.

One type of electrical igniter is shown in Fig.10a: this consists of a ceramic body heated from a 6 volt source. This is able to ignite an initial flow of 0.2 lb/sec of red fuming nitric acid/gasoline 15 seconds after switching on. No tests, however, have been made with the propellants below ambient temperature.

To ignite white fuming nitric acid and aviation fuel JP.3 two opposed hollow cone spray nozzles and a glow plug have been used, arranged as shown in Fig.10b. In this case an initial flow of 0.05 lb/sec of propellant is ignited in 0.8 sec. 24 volts are used initially to heat the plug, but the supply is reduced automatically to 6 volts when the plug is heated. The resistance wire used for the glow plug is 0.030 in. diameter.

Another method of electrical ignition is to use the glow plug merely to vapourize the propellants and to ignite the vapour by an electric spark. Preliminary tests with a flow of propellants of 0.04 to 0.05 lb/sec have been successful.

5.4 M.W. Kellogg Co.

This firm is investigating various methods of ignition for the A.T.O. unit (see Appendix II) using white fuming nitric acid/aviation fuel JP.3. The following means of ignition have been considered and pursued under the development contract.

Chemical additives to acid

No progress has been made with this method and it is now considered that the possibility of success is remote.

Spark ignition

The ignition of fuel/air mixtures is quite simple, but efforts to ensure the ignition of liquid fuel/acid by spark have not been promising. Propellants with a flow rate of 0.003 lb/sec have been ignited, but the acid tends to corrode the leads and short circuit the spark.

Ignition by heat source

Vapourization of the propellants to their self-igniting temperature has been considered. For this the acid must be heated to 700°F, and when the energy limit is set at 1000 watts the propellant through-put for the igniter does not exceed about 0.001 lb/sec.

Various types of heated surface have been tested. The first arrangement, embodying a glow plug and two hollow cone sprays which communicate directly with the main combustion chamber, is shown in Fig.10c. The plug was wound with platinum wire, and the ignition of propellants at an input rate of 0.01 to 0.02 lb/sec could be obtained with 200 - 250 watts.

The life of the glow plug was short, however, although it could be increased by shielding the plug with perforated metal; the unheated walls of the igniter chamber are an additional disadvantage, and the igniter has also to withstand full combustion chamber pressure. This igniter operated quite satisfactorily with white fuming nitric acid/gasoline, but not when aviation fuel JP.3 was used in place of gasoline.

These results led to the igniter chamber shown in Fig.10d which was developed to give a pressure of about 50 lb/sq in during the ignition period. The ceramic insert in the wall was brought up to working temperature by an intermittent supply of 1000 watts or a continuous supply of 500 watts in 15 to 30 seconds; propellants with a flow rate of 0.1 lb/sec could then be ignited. The maximum possible size of choke has to be used to avoid hard starts and erosion; in normal conditions a pressure of 30 to 50 lb/sq in was developed in the igniter chamber. The igniter functioned correctly when the propellants and the metal parts were cooled down to -35°F : it also functioned when the motor was positioned to fire vertically upwards, and over a range of mixture ratios from 2/1 to 9/1. An endurance of over 100 starts has been obtained from a single igniter, but trouble has been experienced with cracking of the ceramic insert.

To provide an adequate flow of propellants, however, to fire the main combustion chamber of 5000 lb thrust it was necessary to obtain a supplementary supply from a booster. The igniter chamber and booster are arranged as shown in Fig.10c. The booster operates satisfactorily with a propellant flow of 1 lb/sec at a temperature of -35°F . Most of the combustion takes place outside the booster chamber i.e. in the main combustion chamber: the pressure developed is about 6-8 lb/sq in, and with a booster propellant feed of 0.5 lb/sec, a main propellant flow of 15 lb/sec has been ignited successfully many times. The igniter chamber and booster are both uncooled. Solid cone sprays are preferred to hollow cone sprays for the booster as better atomization is obtained. Ignition tests with chambers of 5000 lb thrust (flow rate about 25 lb/sec) have not yet been carried out. Future work is to be directed either to the elimination of the booster or to combining it with the igniter.

6 Combustion chamber design

The majority of the regeneratively cooled combustion chambers that were seen were of fairly conventional type, and either machined or fabricated from pressings. Two exceptions were chambers seen at the Jet Propulsion Laboratory and at Reaction Motors Inc. The chamber at the Jet Propulsion Laboratory consists of an inner shell made with axially formed corrugations brazed or welded to the outer jacket, the coolant flows axially along the passages formed by the corrugations. This type of construction is very light and a chamber giving 2500 lb thrust weighs only 12 lb complete with injector. Chambers of this type have operated quite successfully, and the method of construction appears very promising as it provides a chamber with both a light weight and a thin (0.020 in) inner wall.

The chamber at Reaction Motors Inc. consists of a number of tubes of approximately rectangular cross section which run axially from end to end of the chamber and are shaped to its contour. These tubes are held together by an outer jacket formed by spraying metal on to the outside of the tubes. The coolant is arranged to pass down alternate tubes and up the adjacent ones. Because of the low strength of the sprayed metal the outer jacket has to be relatively thick which makes the chamber heavy, but the inner wall produced by this method of construction is quite thin (0.025 in).

Of the uncooled chambers those employing a ceramic lining and venturi nozzle made of Niafrax (a silicon carbide material) appear to give the best results; firings lasting up to 2 minutes have been obtained with no sign of erosion. The weight of this type of chamber is at present about 50% higher than that of a conventional regeneratively cooled chamber of the same thrust, but, although some improvement may be effected, it seems doubtful whether the weight of this type can ever be reduced to that of the best regeneratively cooled chamber.

6.1 Jet Propulsion Laboratory - axial flow or corrugated chamber

This type of chamber which is now under development provides a light and fairly cheap form of construction together with a thin inner wall giving good heat transfer characteristics. The outer shell is of orthodox shape and is sufficiently thick to withstand the internal stresses. The coolant flows axially down the chamber along a number of passages or corrugations formed of thin metal which is welded or copper brazed to the inner surface of the outer shell. Brazing is used in addition to welding in order to obtain better contact between the inner and outer shells so as to improve heat transfer. It has not been established, however, whether brazing is necessary because so far only fuel has been used for cooling, and there is, therefore, no objection to brazing. (Incidentally, acid has not yet been used for cooling by the Jet Propulsion Laboratory.) If acid were used for cooling, then copper brazing would not be feasible.

Two methods of forming the corrugations have been tried; in one method, which was used to make the 20,000 lb thrust combustion chamber for the Corporal E rocket, the corrugations were pressed in a die; the other method employs hydraulic pressure to distend the internal corrugations; and this has been used to construct a smaller chamber of 2500 lb thrust. The two chambers are described in more detail in the following paragraphs.

6.11 Corrugated chamber for Corporal E

This chamber is about 11 in diameter and is made from four segmental pairs of pressings. Each pair of pressings consists of an outer shell and a corrugated inner shell. The sequence of operations for manufacture consists of pressing each portion, inner and outer, of a segment in its respective die, seam, or spot welding them at 2 inch intervals and then brazing the inner and outer portions together. The four segments are then welded together and a strap is welded over each of the four longitudinal welds to reinforce them. The arrangement is shown in Fig. 11. Some trouble has been experienced owing to the brazing metal melting and running into the joints when the four segments are being welded together; methods of preventing this are being investigated. One method would be to defer the brazing operation until the four segments are welded together, but the firm do not at present possess a large enough brazing furnace. Another method is to employ butt jointing as described in para. 6.12.

The material used for outer and inner shells is mild steel in thicknesses of $\frac{1}{8}$ in and $\frac{1}{32}$ in respectively. As a measure of protection against attack by the acid from the injector jets, the face of the inner shell in contact with the combustion gases is chromium plated after the completion of the chamber, with the latest injector the acid jets do not touch the chamber walls, and this precaution may turn out to be unnecessary.

A few of the design details of the chamber are given below:-

Characteristic length	$L^* = 40$ in
Chamber diameter/throat diameter	1.42/1
Chamber diameter	11.09 in
Throat diameter	7.66 in
Overall length (including injector)	46.6 in
Coolant	aniline/alcohol
Coolant velocity in corrugations in chamber	35 ft/sec
Coolant velocity in corrugations at throat	50 ft/sec
Permissible variation in cross-sectional area of corrugations	$\pm 10\%$
Internal test pressure for corrugations	1800-2000 lb/sq in
Overall rate of heat transfer	
at 3 sec after start	1.4-1.9 B.Th.U/sq in/sec
at 30 sec after start	1.2-1.7 B.Th.U/sq in/sec

The estimated cost of production of this chamber complete with injector at a rate of about 3000/month is given as 150 dollars each (£50 at the present rate of exchange).

6.12 Corrugated chamber for 2500 lb thrust

This chamber is considerably smaller than the Corporal E chamber and this necessitates a somewhat different manufacturing technique for the following reasons. It is very desirable that the sides of the land of each corrugation shall be radially formed. This is very difficult to achieve in one pressing operation because an ordinary die does not move radially into the segment except along the centre line of the segment. With large diameter chambers as for the Corporal E this effect is not too serious as the curvature of each segment is relatively flat and the width of each mating surface or "land" is relatively large. In smaller diameter chambers, however, the "land" is very small and this in conjunction with the smaller radius of curvature makes it impossible to form the corrugations towards the edges of each segment by purely radial pressure.

This difficulty has been overcome by pressing the "lands" in each segment one by one in succession by means of a die. The segment is then welded to the outer shell and the coolant passage between each land is distended by hydraulic pressure to give the correct cross sectional area for the coolant. The sequence of operation is as follows:-

- (a) Press form the segments of the outer shell. There are four segments but they can be reduced to three.
- (b) Press form the four (or three) segments of the inner shell. The same dies as for operation (a) are used, but the segments are not pressed completely to shape.
- (c) Anneal the inner and outer segments.
- (d) Press together each pair of segments (one inner and one outer) in the same die as for operation (a). Henceforward each pair of segments must be kept as a pair.
- (e) Press a series of longitudinal grooves or "lands" along each inner segment. The appropriate die has only one groove, but has an indexing mechanism to give a correct groove spacing along the pitch circle of the segment within ± 0.010 in.
- (f) Along each land seam weld the inner to the corresponding outer segment.

(g) Weld the pairs of segments together to form the complete combustion chamber.

(h) Apply hydraulic pressure of about 700 lb/sq in to distend each coolant passage in order to form the corrugations on the inner shell. Each coolant passage must be individually flow tested to verify that the flow characteristics are correct.

The design details of a combustion chamber which has been made by this method are given below. The chamber has not yet been tested.

Chamber diameter	6 in
Thrust	2500 lb
Propellants	Red fuming nitric acid/hydrazine
Coolant velocity in corrugations in chamber	25-30 ft/sec
Coolant velocity in corrugations at throat	50 ft/sec
Intended rate of heat transfer at throat	6 B.Th.U/sq in/sec
Material	Monel or 18/8 stainless steel
Thickness of outer shell	0.072 in
Thickness of inner shell	0.020 in
Number of coolant passages	33
Number of segments	3

A cross section of a portion of the chamber is shown in Fig.12 which also shows the dimensions of the corrugations in the inner shell after pressing. The die for the corrugations is made by profile milling. The segments are located in the die by pins at each end of the die and by spring loaded stops at positions corresponding to the throat and rear of the chamber. The spacing of the grooves in each segment are within ± 0.010 in. The inner and outer shells are seam welded together, using a Mallory No.3 9 in diameter upper wheel with a contact width of 0.040 in and a Mallory No.1 $3\frac{1}{4}$ in diameter lower wheel with contact pressure of 700 lb/sq in. The upper wheel will do two complete seam welds per revolution before requiring redressing, which is affected by an attachment to the machine. Both intermittent and continuous seam welding have been tried and little difference is found between them. Brazing is not used.

An alternative method of butt welding the segments together so as to dispense with the strengthening strap is being investigated. In this method one of the lands of the corrugated inner shell is arranged to terminate at the edge of the segment and then this and the mating edge are trimmed back so that the two mating lands are half the normal width. The segments are then butt welded together so that the join has a land of normal width. This is also shown in Fig.12. The segments are welded together by the argon arc process.

6.2 Aerojet Engineering Corporation - chamber for A.T.O. motor

This chamber is designed to produce 5000 lb thrust and is shown in part section in Fig.13. The inner shell is pressed in two halves and welded together. A coolant guide strip $\frac{1}{2}$ in high is wound helically round the inner shell and secured by a line of continuous welding on one side except at the throat where it is spot welded at about 2 inch intervals. The strip is then machined down to $\frac{3}{8}$ in high. The filling piece at the throat is made from sheet metal pressed and rolled to shape. The outer shell is rolled, welded and fitted over the inner shell. No particular effort is made to keep close tolerances on the width of the

coolant passages and this has caused no ill effects. The throat diameter is maintained within ± 0.045 in of nominal size, and if necessary an expanding mandrel is used to correct the contraction which sometimes occurs after the coolant guide strip is welded on.

This chamber is made of 18/8 stainless steel, but Inconel X, 19/9 DL and L.605 are being considered. During our visit a chamber in L.605 with a wall thickness of 0.078 in was being made.

In the conditions of full thrust 5000 lb and specific impulse 195 - 198 seconds, the temperature rise of the acid coolant is 25°C with an overall heat transfer rate of 0.74 - 0.90 B.Th.U/sq in/sec. The coolant velocity is about 20 ft/sec round the chamber and 35 ft/sec round the throat with pressure loss of about 55 to 60 lb/sq in.

A chamber of the same dimensions but without the helical coolant strip so that the coolant flows axially along the chamber has been constructed and tested. It is presumed that the coolant annulus was reduced to keep the coolant velocity up to a desirable value. The chamber operated quite successfully, but the inner shell collapsed inwardly on shutting down the motor owing to the effect of the coolant pressure on the hot wall; the maintenance of the feed pressure for a few seconds after the motor is shut down is inseparable from the present design of the chamber as the acid shut-off valve is situated down stream from the cooling jacket.

In another type of this size of chamber under construction the inner and outer shells are secured by dimpling and then welding through the dimples. The dimples are spaced about 1 in apart and allow the coolant to flow axially down the chamber. The shells are pressed in two halves.

6.3 Reaction Motors Incorporated - chamber for 'Lark' missile

The motor for this missile has two combustion chambers of 400 lb and 200 lb thrust respectively. The propellants are nitric acid and aniline, the former acting as the coolant. The coolant passages are formed by helical wire spacers of $1/16$ in diameter; the passage consists of a two start helix at the venturi to the beginning of the chamber with a single start helix along the length of the chamber. The coolant velocity is about 25 ft/sec at the throat and 15 - 20 ft/sec along the chamber. The material is stainless steel.

6.4 Reaction Motors Incorporated - chamber for liquid oxygen/JP.3

This chamber is interesting as the propellants are liquid oxygen and aviation fuel JP.3; the fuel is used for cooling. The burner for this chamber consists of 30 injectors similar to the type used in the 'Lark' motor (see para.4.41), but each has six pairs of holes per injector, with one oxidant to one fuel hole. Film cooling is used, $4\frac{1}{2}\%$ of the total propellant flow passing through a number of holes at the upper end of the chamber. Some design and constructional details are given below.

Characteristic length	$L^* = 20$ in
Chamber diameter/throat diameter	2/1
Chamber diameter	7.63 in
Coolant velocity in chamber	15 ft/sec
Coolant velocity at throat	25 ft/sec
Coolant flows axially down the chamber	
Width of coolant annulus	0.075 in
Number of spacer wires	18

Thickness of inner shell	0.085 in
Mixture ratio, oxidant/fuel, overall	2/1
Mixture ratio, oxidant/fuel, at injector	$2\frac{1}{2}/1$
Mixture ratio, oxidant/fuel for optimum specific impulse (theoretical)	$2\frac{1}{4}/1$
Thrust	4000 lb
Specific impulse (91% of theoretical value)	227 lb sec/lb

The material of the outer shell is stainless steel, and the inner shell is made of nickel. The inner shell is spun in three sections, the chamber itself, the convergent portion of the venturi and the divergent portion. These are then welded together and the assembly is given a final spinning.

6.5 Reaction Motors Incorporated - "Spaghetti" chamber

In this design an attempt is made to construct a chamber with a thin inner shell. The chamber and venturi consists of a number of tubes arranged longitudinally which are held together by a jacket formed by spraying metal on to their outside surfaces. The coolant flows down alternate tubes and up the adjacent ones. The tubes are originally of circular cross section manufactured to normal tolerances and formed in a die to the contour of the chamber and to roughly rectangular cross section, as shown in Fig. 14. The wall thickness is reduced somewhat by this process, in a chamber inspected the reduction was from 0.035 in to 0.025 in. The tubes are then assembled on a mandrel to the shape of the chamber and sufficient metal sprayed on the outside to form a jacket thick enough to withstand the working pressure. A thick coating of the order of $\frac{1}{2}$ in is necessary owing to the relatively low tensile strength of sprayed metal. The tubes can be made of stainless steel, nickel, copper or aluminium. Mild steel could be used were it not for the necessity of de-oxidizing it after annealing, unless this operation were carried out in an inert or reducing atmosphere. Stainless steel or aluminium can be used for the outer jacket. The following details refer to a chamber now under investigation by Reaction Motors Incorporated.

Propellants	Liquid oxygen/ammonia
Characteristic length (the chamber is not tubular)	$L^* = 10$ in
Pressure	800 lb/sq in
Thrust	5000 lb
Coolant	Ammonia flowing down one tube and up the adjacent
Tubes	18/8 stainless steel $\frac{3}{8}$ in outside diameter by 0.035 in thick. After forming the thickness becomes 0.025 in
Jacket	Stainless steel $\frac{1}{2}$ in thick

Trouble has been experienced owing to the collapse of the inner wall of some of the tubes towards the outside of the chamber. This is attributed to a "hard start" occurring before the fuel pressure in the tubes has reached its normal value. At present the fuel shut-off valve is located upstream from the coolant jacket, but it is under consideration to locate it downstream in order to ensure full jacket pressure before firing.

6.6 Reaction Motors Incorporated - chamber for "Neptune" motor

A few details of this chamber are:-

Propellants	Liquid oxygen/ethyl alcohol
Characteristic length	$L^* = 57$ in
Thrust	20,000 lb
Diameter of chamber	16 in
Diameter of chamber/diameter of throat	approx. 2/1
Thickness of inner shell to throat	0.125 in
Thickness of inner shell from throat to end of nozzle	0.1875 in

6.7 M.W. Kellogg Co. - chamber for A.T.O. motor

A sketch of this chamber designed for a thrust of 5000 lb is shown in Fig.15. The inner and outer shells are fabricated from pressings and the two are welded together through a series of dimples formed in the outer shell. The dimples are spaced at about one inch intervals longitudinally and circumferentially and the location is arranged so that the coolant flow is axial. The dimples are of the minimum size which permits efficient spot welding at a pressure of 1600 to 2000 lb/sq in.

For the chamber design a 'gas wall' temperature of 1760°K (3200°R) is assumed with a 'liquid wall' temperature just below the local boiling point of the nitric acid coolant. The coolant entry temperature was assumed to be 77°C in accordance with the specification, but this requirement has been relaxed and a lower temperature is now permissible. No effort has been made to reduce the value of L^* to a low figure in this chamber, as attempts to do so in a chamber of 500 lb thrust with the same type of injection were unsuccessful.

Some design details are as follows:-

Characteristic length	$L^* = 70$ in
Thrust	5000 lb
Chamber diameter/throat diameter	2.25/1
Chamber diameter	8 in
Propellants	White fuming nitric acid/aviation fuel JP.3
Coolant	White fuming nitric acid flowing axially along chamber through an annulus 0.065 in wide
Coolant velocity along chamber	25 ft/sec
Coolant velocity at throat	40 ft/sec
Coolant pressure drop	100 lb/sq in
Thickness of inner shell	0.078 in
Material	18/8 stainless steel

6.8 Combustion chamber design parameters

Very little information was obtained on the effects of the ratio of the chamber diameter, D_C , to the throat diameter, D_T , and of the ratio of the length, L , to the chamber diameter, D_C , upon the performance of the motor. The ratio of D_C/D_T for the majority of the chambers that were seen was about 2/1. The choice of this value appears to be a compromise between the stowage space requirements for the missile, the strength of the material used for the inner shell, and conformity with existing practice; considerations of combustion efficiency appear to play little part in formulating the decision. It is, however, very difficult to determine the precise effect of the parameters indicated above because other factors such as the type of injector can have such a big influence on performance. Nevertheless, it is thought by Aerojet Engineering Corporation that these factors can be isolated, and a programme of work on this subject is under consideration.

7 Cooling the combustion chamber7.1 Nitric acid cooling

There appears to be no difficulty in cooling the combustion chamber of a nitric acid/kerosine motor with nitric acid. Very little work is being done with this combination of propellants but two motors working on this system were seen, one at Aerojet Engineering Corporation (see para.6.2) and the other at M.W. Kellogg Co. (see para 6.7). Some relevant details are:-

	<u>Aerojet</u>	<u>Kellogg</u>
Thrust	5000	5000 lb
Characteristic length L^*	45	70 in
Chamber diameter	6.25	8 in
Coolant velocity in chamber	20	25 ft/sec
Coolant velocity at throat	35	40 ft/sec
Pressure drop through cooling jacket	55/60	100 lb/sq in
Coolant temperature rise	23	- °C
Thickness of inner shell	0.093	0.078 in
Material of inner shell	18/8 stainless steel	

The thickness selected for the inner wall is a compromise between the claims of adequate strength and efficiency of heat transfer, and in both these chambers it is insufficient to withstand the pressure of the acid in the cooling jacket immediately after shut down when the chamber is hot. The Aerojet Engineering Corporation, therefore, provides a thin strip $\frac{3}{8}$ in high, wound helically round the chamber primarily to act as a channel for the coolant, but also to add strength (see para.6.2), and the Kellogg Co. strengthens the inner shell by welding it to the outer one through a large number of dimples formed in the outer shell (see para.6.7).

Acid cooling is also used in the 'Lark' motor which has two chambers giving 400 lb and 200 lb thrust respectively. Aniline is used as the fuel, but the combustion temperature is comparable to that of kerosine. The coolant velocity is about 15 to 20 ft/sec in the chamber and 25 ft/sec in the throat, whilst the pressure drop is about 30 lb/sq in. The material is stainless steel.

These chambers operate quite satisfactorily with acid cooling, and in each case it was stated that no particular difficulty had been encountered in obtaining these results.

7.2 Sweat cooling

Little work is now being done on sweat cooling. Dr. Pol Duwez of Jet Propulsion Laboratory who has carried out the basic physical and engineering research considers that further progress cannot be made until the production problems of making large pressings of uniform permeability have been solved. Regenerative and film cooling can adequately meet the needs of existing motors, in his opinion, but sweat cooling may be required when very high rates of heat transfer are contemplated.

Small plugs of porous metal of uniform permeability have been produced at the Jet Propulsion Laboratory by laboratory methods, but no success in the production of larger pressings, such as 3 in diameter cylinders of uniform permeability has been achieved. Satisfactory plugs of copper and stainless steel have been made by hot pressing the

powdered metal with ammonium carbonate. No sintered material of aluminium has been made because aluminium requires higher pressures for compaction owing to the presence of a coherent surface film of oxide on the particles.

Sweat cooling appears to work satisfactorily with gases, but it is not entirely successful with liquids. In considering the phenomena two extreme conditions can be visualized. At one extreme the coolant boils on the cool surface of the porous metal, which means that the cool side of the porous metal has a temperature at least as high as the boiling point of the coolant under the pressure conditions at that point, therefore the bulk of the porous metal must be at a higher temperature, and cooling takes place entirely by gas flow through the porous metal. At the other extreme the liquid passes through the porous metal and is evaporated at the hot surface washed by the combustion gases; this is uneconomical as sufficient liquid must be forced through to keep the porous metal everywhere below the boiling point of the coolant. The optimum effect would be obtained by the continuous absorption of heat by the liquid as it passes through the porous metal so that on reaching the hot surface the liquid is all evaporated, thus forming a boundary layer of relatively cool gas on the hot combustion surface. This flow region however is extremely unstable due to the plugging of the pores of the metal by gas or air bubbles which are released from the liquid whilst evaporation is taking place.

Since the tensile strength of a porous metal decreases with increasing porosity, a satisfactory metal should have a high permeability with a low porosity. Generally sufficient permeability can be obtained when the strength is about two thirds that of the solid metal. Small discs of stainless steel of adequate porosity with an ultimate tensile strength of 40,000 lb/sq. in. have been made at the Jet Propulsion Laboratory.

Incidentally, it is suggested that porous metal might be a suitable material for the blading of gas turbines. Tests have indicated that adequate cooling can be obtained by by-passing 1 to 10% (depending on the permissible working temperature) of the total air requirements of a gas turbine through the blades.

8 Shut-down problems

Explosions in the combustion chamber have been experienced by both the Aerojet Engineering Corporation and the M.W. Kellogg Co. immediately after shutting down motors working on nitric acid/aviation fuel JP.3. The explosions occurred within a few seconds of shutting down and were attributed to the propellants contained in the injector head and the pipe lines dribbling into the chamber. To overcome this difficulty the M.W. Kellogg Co. have complicated their type of injector head by the incorporation of anti-dribble valves behind each jet (see para.4.61). Both firms use fuel and oxidant shut off valves which are mechanically coupled together and which have a relatively long time of opening, at least 0.5 seconds, and, therefore, a similar time of closing. A shut off system similar to this has recently given trouble at R.P.D. and a cure was effected by reducing the valve closing time from 0.4 to 0.13 second.

Although this problem has not up to the present proved serious in Great Britain, there is little doubt that it is regarded as a major difficulty in the United States.

9 Gas production for propellant feed systems

9.1 Jet Propulsion Laboratory

The work done at the Jet Propulsion Laboratory on generating gas by injecting aniline into nitric acid is described in reports which are available in Great Britain. In addition, however, the development of a generator to produce gas from hydrazine for the propellant feed system of the Corporal E motor has been nearly completed and this generator is described below.

95 - 97% Hydrazine/water is used to produce oxygen/steam by catalytic decomposition. The decomposer consists of a 2 in bore mild steel tube having an internal volume of 70 cu in packed with catalyst stones. The catalyst stones are made by saturating porous alumina pellets with a solution containing an equimolecular mixture of iron, cobalt and nickel nitrates and then heating the saturated pellets to remove the nitrogen peroxide leaving the metal oxides. The oxides are then reduced to the metals by hydrazine.

This catalyst does not operate below about 500°F and, therefore, decomposition has to be initiated by heating the catalyst by means of a subsidiary supply of nitrogen tetroxide/hydrazine for 0.3 sec; in this process about 10 cc of nitrogen tetroxide is used. Nitric acid will be used instead of nitrogen tetroxide in the Corporal E missile. At the working pressures of 400 - 750 lb/sq in the generator gases contain a considerable proportion of ammonia. A Haber-type catalyst is, therefore, added downstream from the main catalyst, and the amount of ammonia is thus reduced to about 20 molar per cent. It is considered by the Jet Propulsion Laboratory that the amount of ammonia cannot be reduced much below this value at these operating temperatures. Each cubic foot of catalyst will produce about 600,000 cu ft of gas.

In theory this generator should be slightly more than twice as efficient as an H.T.P/steam generator operating at the same gas pressure. In practice it is found to be 70 - 80% more efficient. The gas temperature is 1300 - 1400°F and has to be reduced to 400°F for use in the Corporal E motor feed system. This is to be effected by a heat exchanger in which the acid oxidant is to be used as the coolant. It is of interest to note that the gas generator chamber operates at cherry red heat.

The ignition mixture of nitrogen tetroxide/hydrazine is intentionally fuel rich (ratio 0.4/1) to keep the combustion temperature low, as a high temperature leads to fusion of the catalyst stones. The generator can be started in 0.06 sec, but in these conditions some hydrazine passes through the generator without decomposition. In normal operation the catalyst stones are reduced throughout their mass and not merely on the surface.

The final weight of the gas generator for the Corporal E missile⁵ is estimated to be 125 lb which includes the heat exchanger, the hydrazine and the pressure gas for feeding the hydrazine. This weight is much less than that of the corresponding acid/aniline pressurizing system.

9.2 Aerojet Engineering Corporation

This firm has had experience with both solid and liquid propellant gas generators. It is stated that when the gas is applied directly to pressurize the acid oxidant there is a degree of reaction which causes excessive variation in the feed pressure if the temperature of the acid varies. It was remarked in the United States Department of Defence that

in some cases the gases produced by this type of interaction between the pressurizing gas and the oxidant supply about half the feed pressure. This behaviour has occurred with the solid propellant Aeroplex K. There is, however, little reaction between nitric acid and the solid propellant A.K.253 based on ammonium perchlorate, of which the products are fully oxidized. Although the temperature of the generated gas is 3400-3900°F, its temperature in the acid tank is reduced to about 1000°F owing to the thermal capacity of the tank and the evaporation of the acid. For a tank wall $\frac{1}{4}$ in thick, the maximum temperature of the outside of the wall is about 500°F and there is no appreciable change in the bulk temperature of the acid.

Some experiments have been made on cooling the generator gases with nitrogen. Red fuming nitric acid/aniline at a mixture ratio of 1.5/1 to 2/1 produces gas at a temperature of 2500°F; a somewhat lower temperature is obtained by the use of white fuming nitric acid/aviation fuel JP.3 at the same mixture ratios. About 1.5 to 2 times as much nitrogen as propellant is introduced near the injectors and this has the effect of lowering the gas temperature in an acid tank with walls $\frac{1}{4}$ in thick to about 500°F. The outside wall temperature is about 150°F and the bulk of the liquid shows no appreciable rise of temperature. Such a system has been used to feed propellants to a 2500 lb thrust red fuming nitric acid/aniline motor for 45 seconds. It is claimed that a generator system using nitrogen gas as a diluent and coolant is appreciably lighter than a nitrogen gas pressurizing system; the saving is said to be about 35% when the propellant tanks are included in the total weight of each system.

White fuming nitric acid/aviation fuel JP.3 at a mixture ratio as low as 0.8/1 has been used successfully for gas generation. Combustion is quite good, but the gases contain some unchanged hydrocarbons; the gas temperature is about 1500°F.

Some gas generators which are essentially scaled down combustion chambers with impinging jets at their circumference have been developed. The chambers are regeneratively cooled with fuel and their diameters are $2\frac{1}{2}$ -3 inches. The gas temperature is 1500°F, but it is not yet certain that cooling is necessary although there is the problem of heat transfer to the injector. It is estimated that the generator of this type required for a motor of 4000-5000 lb thrust is equivalent to a combustion chamber giving 300 lb thrust. The characteristic length L^* of these generators is 100 in.

Work has also been done on the use of hydrazine with a stainless steel catalyst. Gas temperatures of 1000-1500°F have been obtained with a mixture of 85% hydrazine/15% methanol, but the operation of the generator is erratic. The system sodium borohydride/water has also been considered as a gas producer.

10 Conclusions

As a result of this most interesting visit the following main conclusions are drawn concerning the rocket motor policy of the United States.

- (1) Considerable emphasis is placed on rocket assisted take off units for aircraft, and these are required for repeated operation.
- (2) The agencies working on missile development have not received detailed Service requirements, particularly for long term storage, and much of their work must be regarded as test vehicle development. A

critical review of the best propellants for specific Service use has, therefore, not yet been undertaken, particularly with respect to hypergolic or non-hypergolic combinations.

(3) More work is being done with a view to the design and development of long range strategic weapons than in the United Kingdom.

(4) It appears that the problem of propellant storage and supply is not the responsibility of the motor designer, but that of the designer of the vehicle. Most vehicle design is being done by the United States aircraft industry which was not visited by this mission.

(5) Although no particular rocket motor was seen, which would satisfy British Service requirements, there is no doubt that much work has gone into the design, development and production of ancillary equipment such as valves, turbines, pumps, pressurizing systems, etc.

(6) Nothing outstandingly new was seen in actual rocket motor design with the exception of the Jet Propulsion Laboratory axial flow combustion chamber described in this note. However, it appears that the United States research and development organizations could produce a very good operational rocket motor based on nitric acid, provided that the best ideas of these agencies were combined.

(7) The general conclusion of the mission is that, at the present state of development, the best all round design of nitric acid rocket motor would include an impinging jet type of injector, a regeneratively cooled combustion chamber operating at a pressure of about 20 atm and according to the size of the motor, a propellants feed system using either pressurized tanks or a turbo pump unit.

11 Recommendations

It was impossible for the mission in the short time available to form really detailed conclusions on the state of rocket motor development in the United States and it is recommended that technicians should be interchanged with American agencies to ensure continuous liaison. If this is impracticable then at least one rocket motor engineer should be attached permanently to the British Joint Services Mission to cover this type of work.

Acknowledgements

It is desired to acknowledge the help given at all times by members of the United States rocket authorities whose co-operation left nothing to be desired.

The arrangements made by the B.J.S.M. for the visits and accommodation were excellent and it is desired to place on record the special thanks of the authors to Dr. L. Phillips of the British Joint Services Mission.

SECRET - DISCREET

Technical Note No. R.P.D. 39

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<u>No.</u>	<u>Author</u>	<u>Title, etc.</u>
1	John L. Sloop	Problems relating to rocket engineering. N.A.C.A. Conference on Aircraft Propulsion Systems Research, Washington. January 18th/19th 1950.
2	Major N.M. Harris R.E.M.E.	The guided AA rocket "Enzian" RAE/RPD Report No. 6/47. September, 1947.
3	P.M. Ordin, R.O. Miller J.O. Diehl	Preliminary investigations of hydrazine as a rocket fuel. N.A.C.A. Research Memorandum No. RME. 7H21 Washington. May 24th 1948, p.5.
4	F.B. Stanley	Extrusion of polyethylene film. "Modern Plastics" Vol. 26 No. 12 pp. 97-102 New York. August, 1949.
5	L.G. Dunn, P.J. Weeks F.G. Denison	The present status of the Corporal E development. J.P.L. Memo. No. 4-59. March 17th, 1950.

Attached

Drg. R.P.D. 483 - 492

Advance Distribution

CS(A)	
Chief Scientist	
P/DSR(A)	
ADSR(Gen)	
DGWRD	
GW3 Cmdr Ashworth	6
D Eng RD	
Eng RD6	
Chairman ADB	
ERDE Waltham Abbey	6
ADGW(R & D)	
TPA3/TIB	80
<u>R.A.E.</u>	
Director	
G Weapons	3
Mat Dept	
Chem Dept	
Armament Dept	
Library	

APPENDIX IReference index to rocket motor establishments

<u>Agency, Establishment</u>	<u>Paragraphs in which Products or projects are mentioned</u>
Aerojet Engineering Corporation	3.2.2, 3.3, 3.4.3, 4.1, 4.3, 5.2, 6.2, 6.8, 7.1, 8, 9.2
Jet Propulsion Laboratory	2.5, 2.6, 2.7, 3.2.1, 3.4.2, 4.2, 6, 6.1, 7.2, 9.1
M.W. Kellogg Co.	2.2, 2.4, 3.3, 4.6, 6.7, 7.1, 8,
Naval Air rocket test station	4.5
Reaction Motors Incorporated	4.4, 6, 6.3, 6.4, 6.5, 6.6
United States Air Force Material Command H.Q. Wright Field	3.4.1

APPENDIX IIDetails of assisted take off motor

These details for the assisted take off rocket motor model 649 for the Boeing B47 aircraft were given by the M.W. Kellogg Co. Development contracts for this project have been placed both with this company and with the Aerojet Engineering Corporation. Some particulars are given below.

Total thrust

20,000 lb for 60 sec obtained from four constant thrust motors (each 5000 lb thrust), regeneratively cooled with white fuming nitric acid. The normal output of each motor is 4000 lb, with an available maximum of 5000 lb. The motors are arranged in two pairs, one on each side of the aircraft; there is one air driven turbine for each pair of motors.

Propellants

White fuming nitric acid (U.S.A.F. Spec. 14104) Aviation Fuel JP.3 (Spec. A.N.-F-58) or Aviation gasoline (Spec. A.N.-F-48a).

Services

Air at 2500 lb/sq in operating pressure for controls, D.C. electrical supply at 24 volts (on aircraft).

Propellant Consumption

0.0054 lb/sec/lb of thrust (M.W. Kellogg Co. obtains 0.00523 lb/sec/lb at 4000lb thrust and 0.00499 lb/sec/lb at 5000 lb thrust).

Weight

Originally specified at 70 lb; actual weight 83.5 lb. These figures are for each assembly and include the combustion chamber, valves, injectors main propellant valves and ignition system.

Combustion Chamber and Injector

See paras. 4.6.1 and 6.7 respectively.

Operating Conditions

Lowest operating temperature, -35°F . Either 10,000 or 20,000 lb maximum thrust can be selected by the aircraft pilot. Other changes in thrust level have to be made during servicing. Full thrust is required within 5 seconds of operating the firing switch. It must be possible to restart 5 times without servicing.

At 5000lb thrust,

Propellant consumption = 23 lb/sec

Mixture ratio = 3.5/1,

Chamber pressure = 350 lb/sq in (abs)

Effective specific impulse = 215 lb/sec/lb

At 4000 lb thrust,

Propellant consumption = 19.7 lb/sec

Mixture ratio = 3.5/1,

Chamber pressure = 290 lb/sq in (abs)

Effective specific impulse = 203 lb/sec/lb
Propellant consumption of ignitor 0.1 lb/sec
Propellant consumption of ignitor booster 1 lb/sec

Expulsion system

Two air driven turbo-pump units, one for each pair of chambers. Each turbo-pump unit develops about 160 H.P. To prevent cavitation the oxidant tank is slightly pressurized by air. The fuel tank is not pressurized, but has an electrically driven booster pump at the outlet to the tank; the reason for this difference is that a booster pump was available for the fuel but not for the acid.

The filling point for the acid and fuel tanks is situated downstream from the combustion chamber and thus ensures that the acid lines and coolant jacket are filled.

Fuel pump - 125 gallons/min at 515 lb/sq in (abs)
Minimum inlet pressure 21 lb/sq in (abs)
Maximum temperature 110°F

Acid pump - 190 gallons/min at 640 lb/sq in (abs)
Minimum inlet pressure 32 lb/sq in (abs)
Maximum temperature 160°F

Maximum turbine air consumption 3.58 lb/sec
Turbine speed = 17,000 r.p.m.
Overall efficiency 38 - 42%.

Main propellant valves

In the main valves (one per combustion chamber) the acid and fuel valve are coupled mechanically together. A pintle of decreasing diameter regulates the propellant flow to give a build-up time of about 2 seconds. The valve is operated by the fuel. The seats are stellite working on stellite. The acid valve is fitted downstream from the coolant jacket.

Firing the motor

Two switches are used for firing the motor namely an arming switch and a firing switch.

Arming switch. The function of this switch is to pressurize the oxidant tank, energize the igniter coils (these take 15 - 30 seconds to become warm) and open the liquid valves at the outlets to the tanks. A light in the pilots cockpit indicates when this has been done.

Firing switch. This opens the air control valve and starts the turbine; it also opens the igniter valves, and when the correct pressure in the igniter chambers has been reached, opens the main propellant valves. Full thrust must be reached within 5 seconds of operating the firing switch.

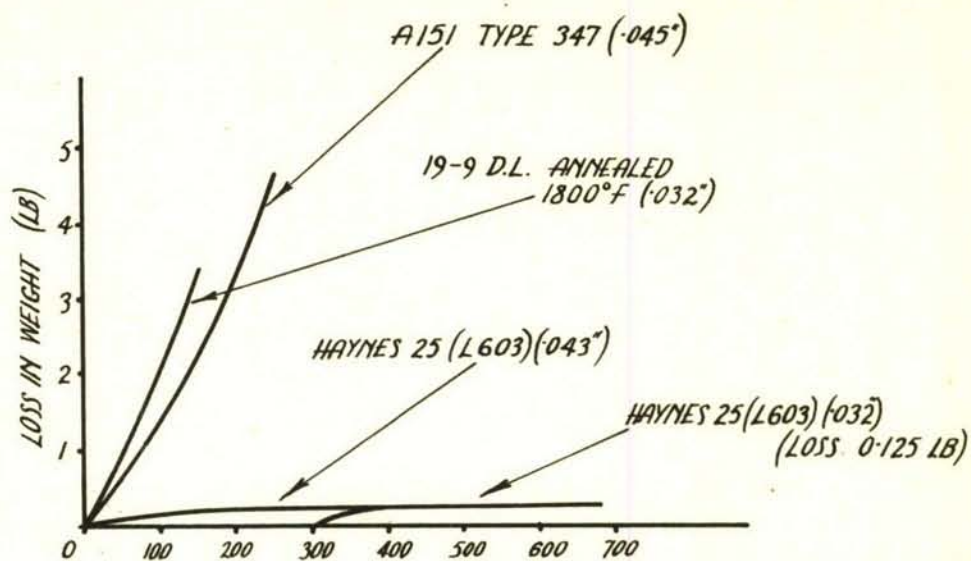


FIG.1. CORROSION OF TANKS BY WHITE FUMING NITRIC ACID

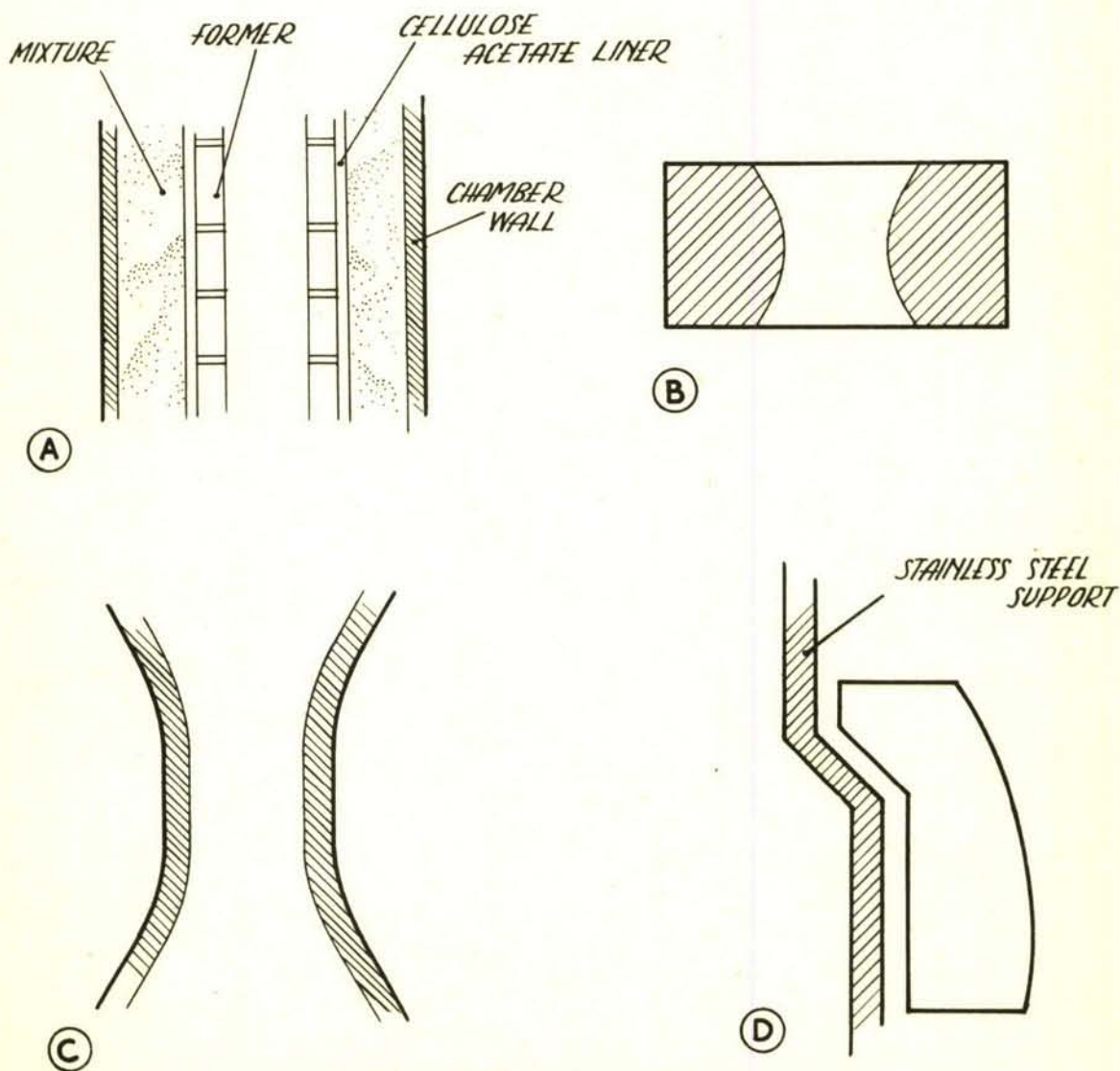
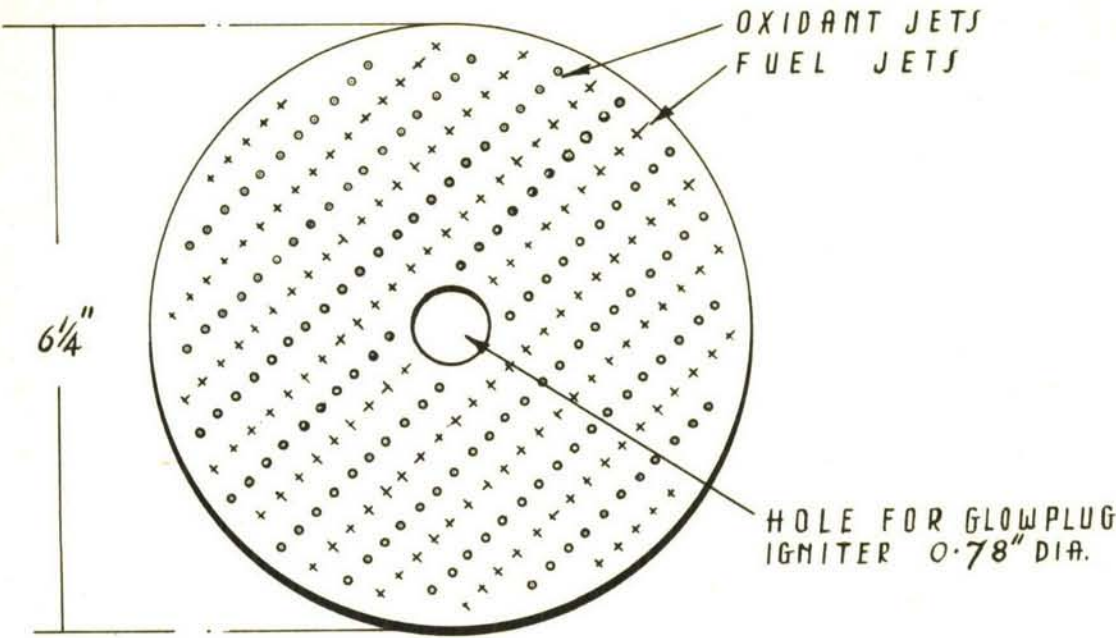
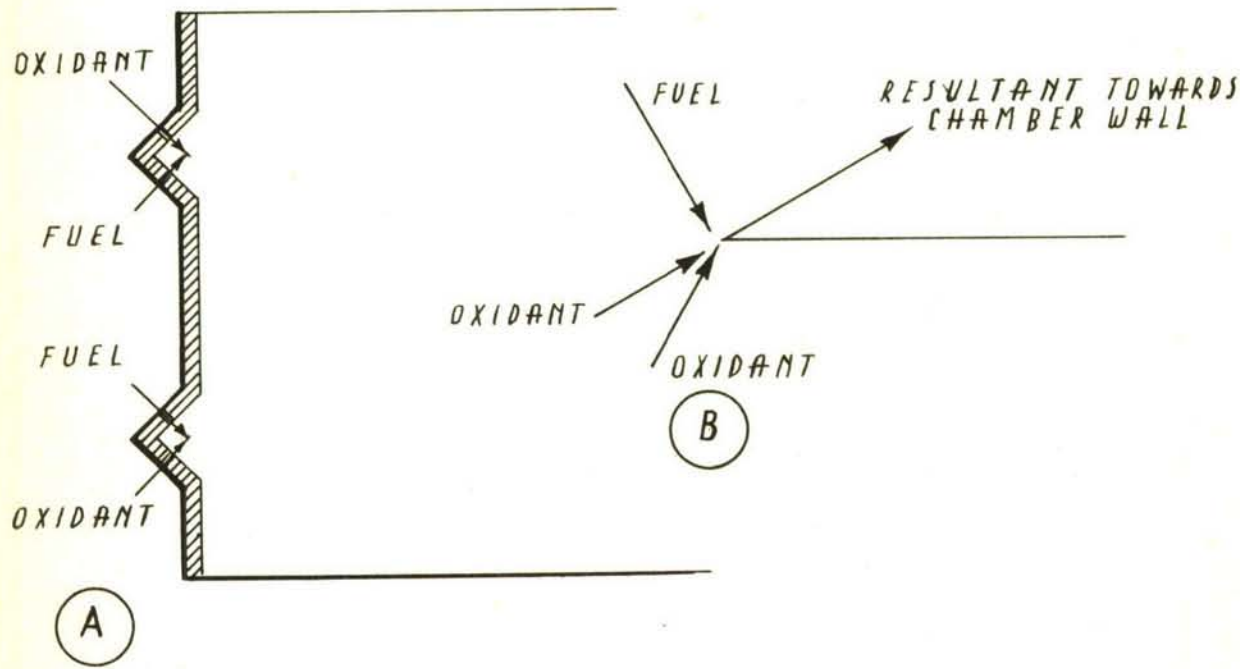


FIG.2. CERAMIC LINERS AND VENTURI NOZZLES



Approximately 170 Fuel Jets
" 140 Oxidant Jets
Thrust - 5000 lb
Propellants - White Fuming Nitric Acid/J.P.3

FIG.3. MULTIHOLE OR "SHOWER HEAD" INJECTOR
FOR A.T.O. MOTOR



SCHEMATIC ONLY

FIG.4. DIAGRAMS OF JET ARRANGEMENTS FOR
EXPERIMENTAL INJECTORS

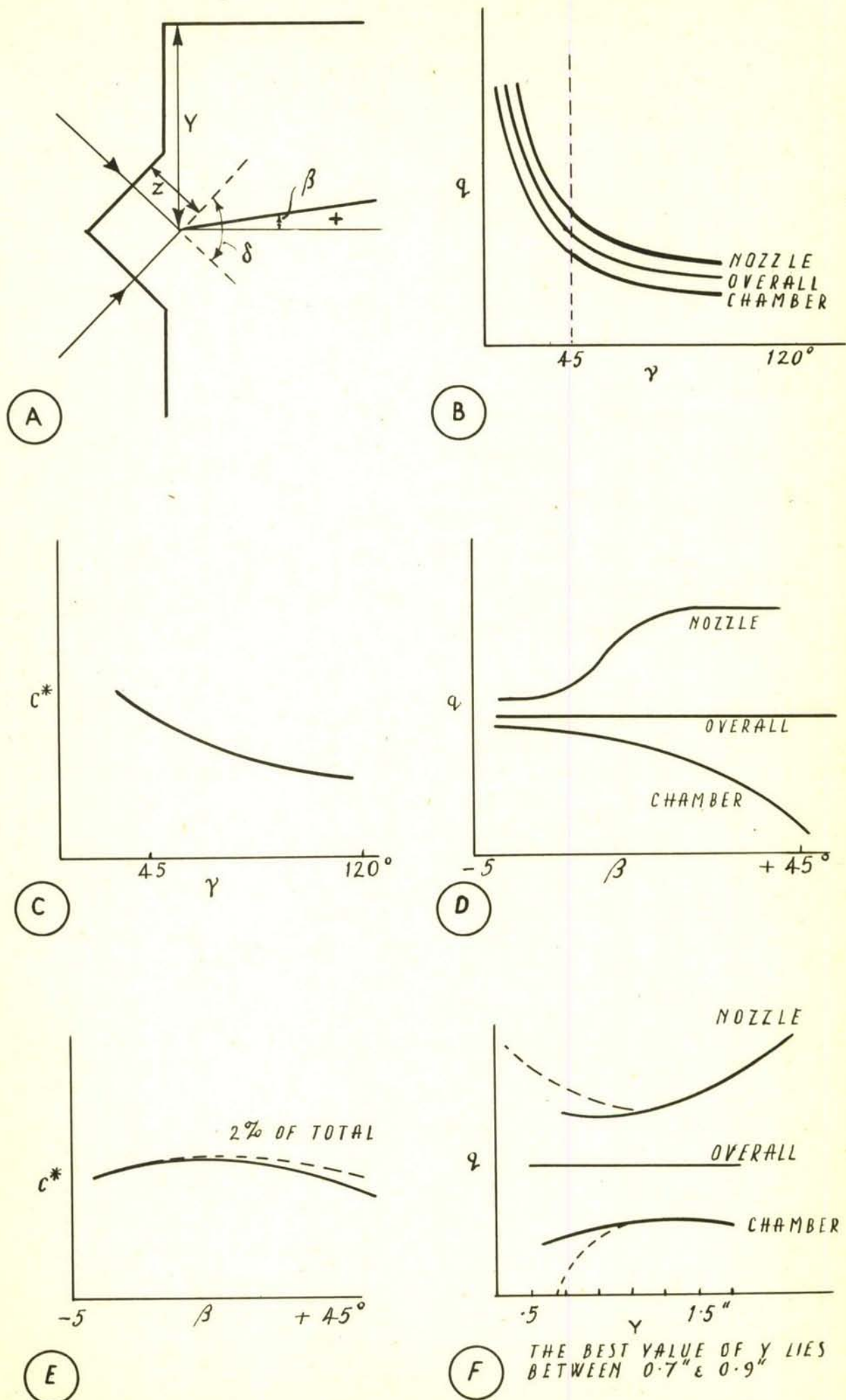


FIG.5. EFFECT OF INJECTION PARAMETERS

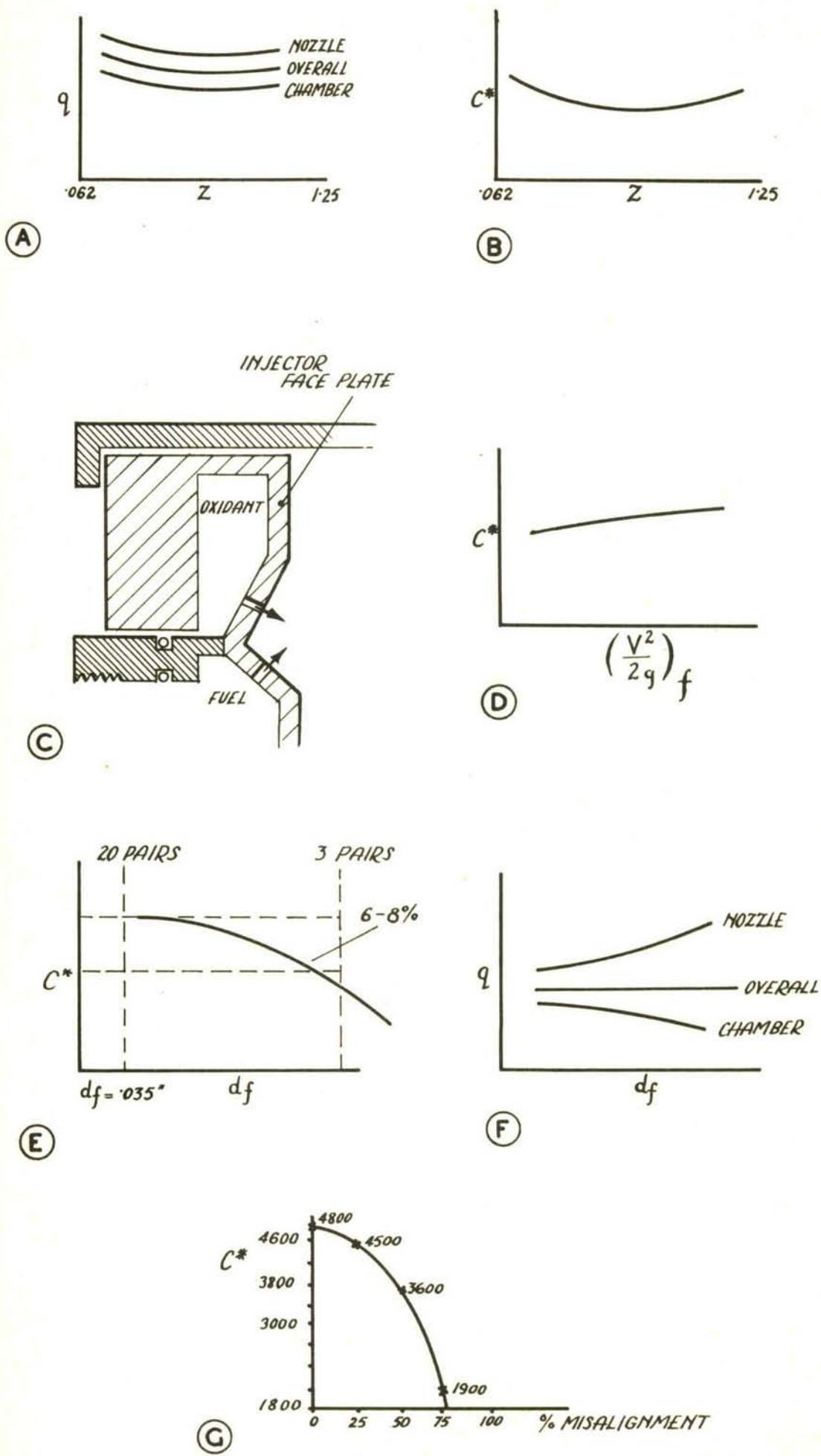
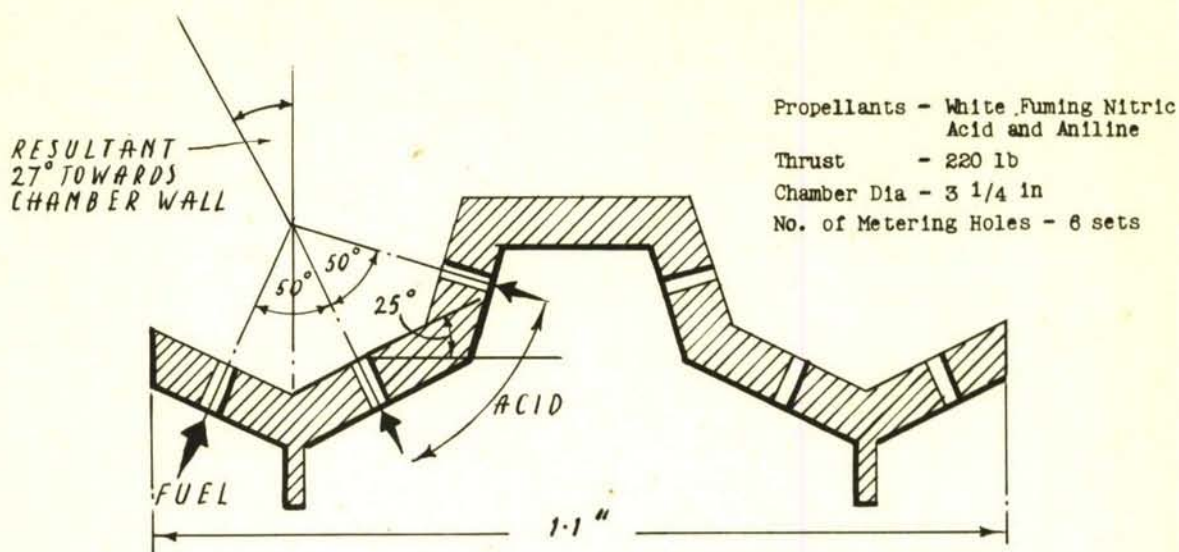


FIG.6. EFFECT OF INJECTION PARAMETERS (Cont'd.)



ACID HOLES. Pilot ream to 0.0595" - 0.0610" and then tap out to get a flow of 0.74 lb/sec water at 60 lb/sq.in.

FUEL HOLES. Pilot ream to 0.0514" - 0.0518" and then tap out to get a flow of 0.27 - 0.285 lb/sec water at 60 lb/sq.in.

FIG.7. "LARK" INJECTOR
(REACTION MOTORS, Inc.)

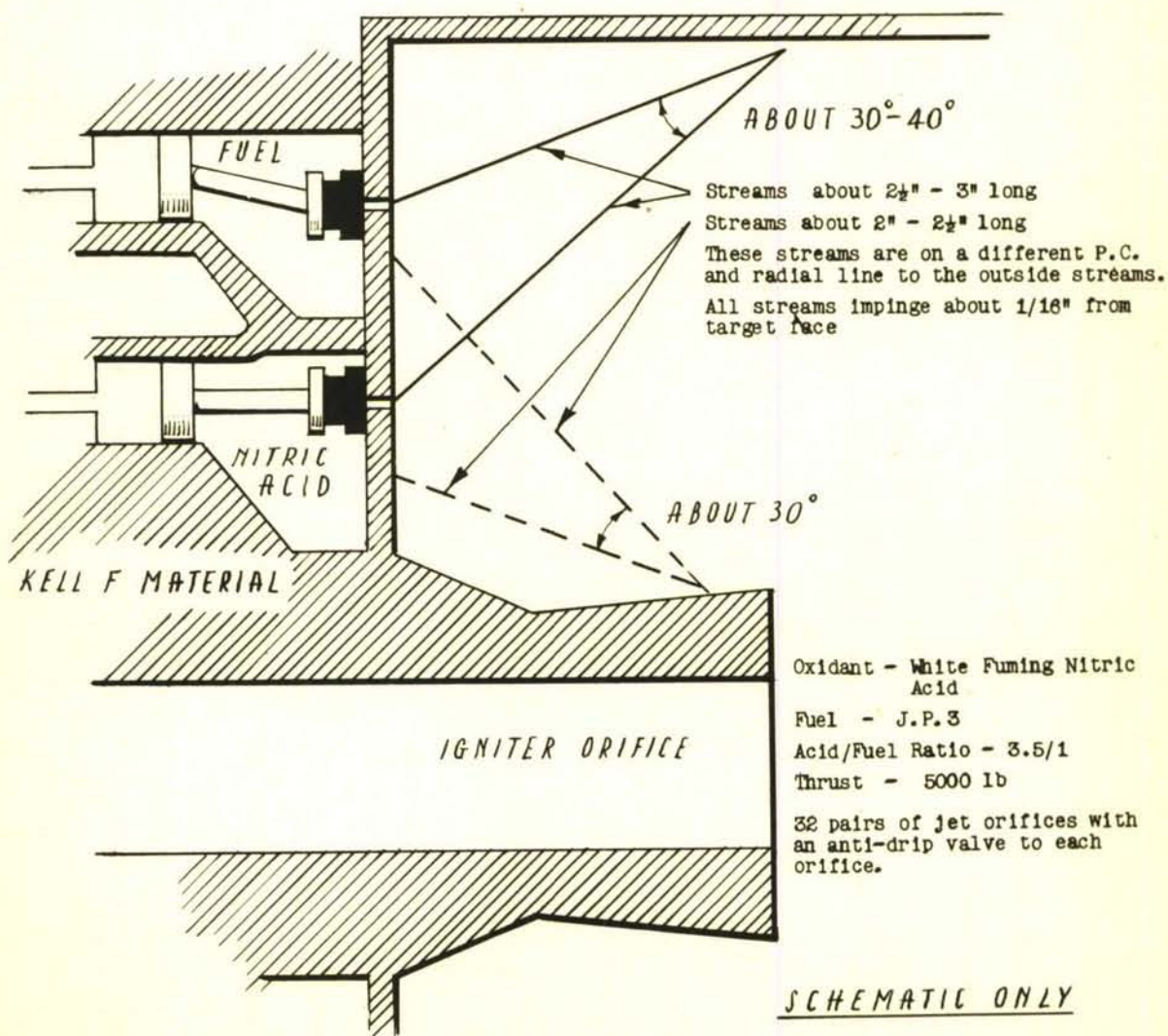


FIG.8. INJECTOR FOR A.T.O. MOTOR
(M. W. KELLOG Co.)

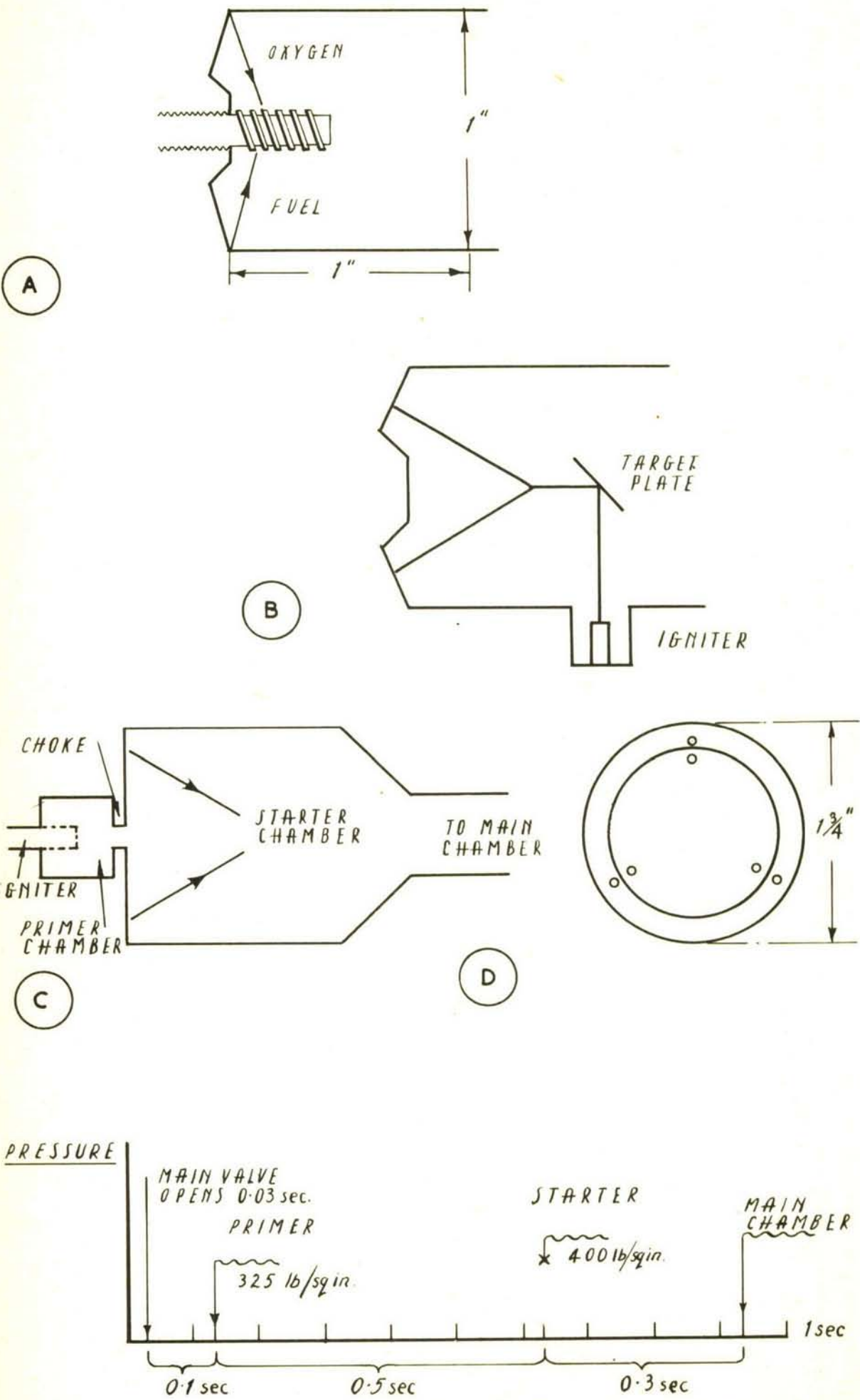


FIG.9. IGNITION ARRANGEMENTS
(AEROJET ENGINEERING Co.)

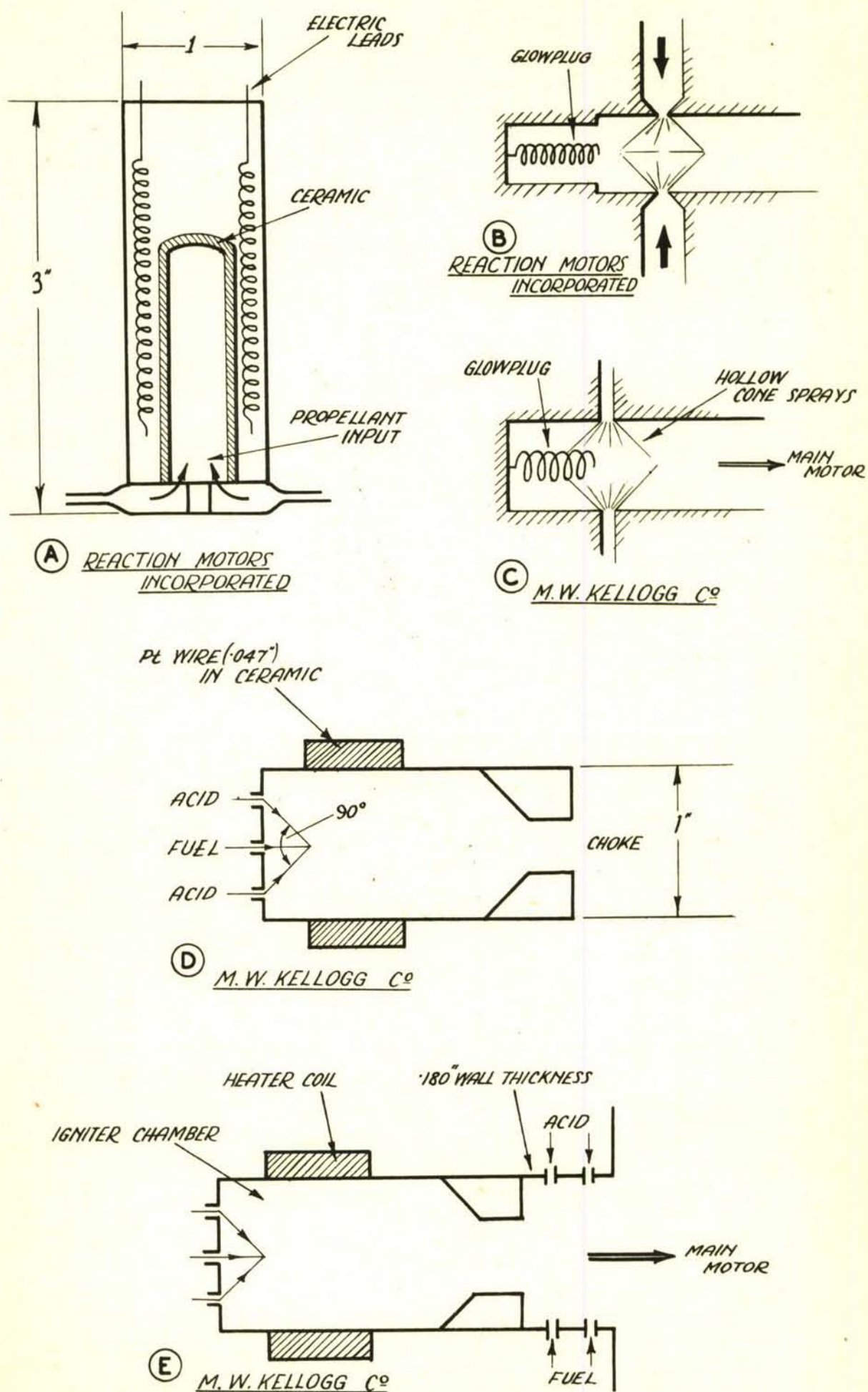


FIG.10. IGNITION ARRANGEMENTS

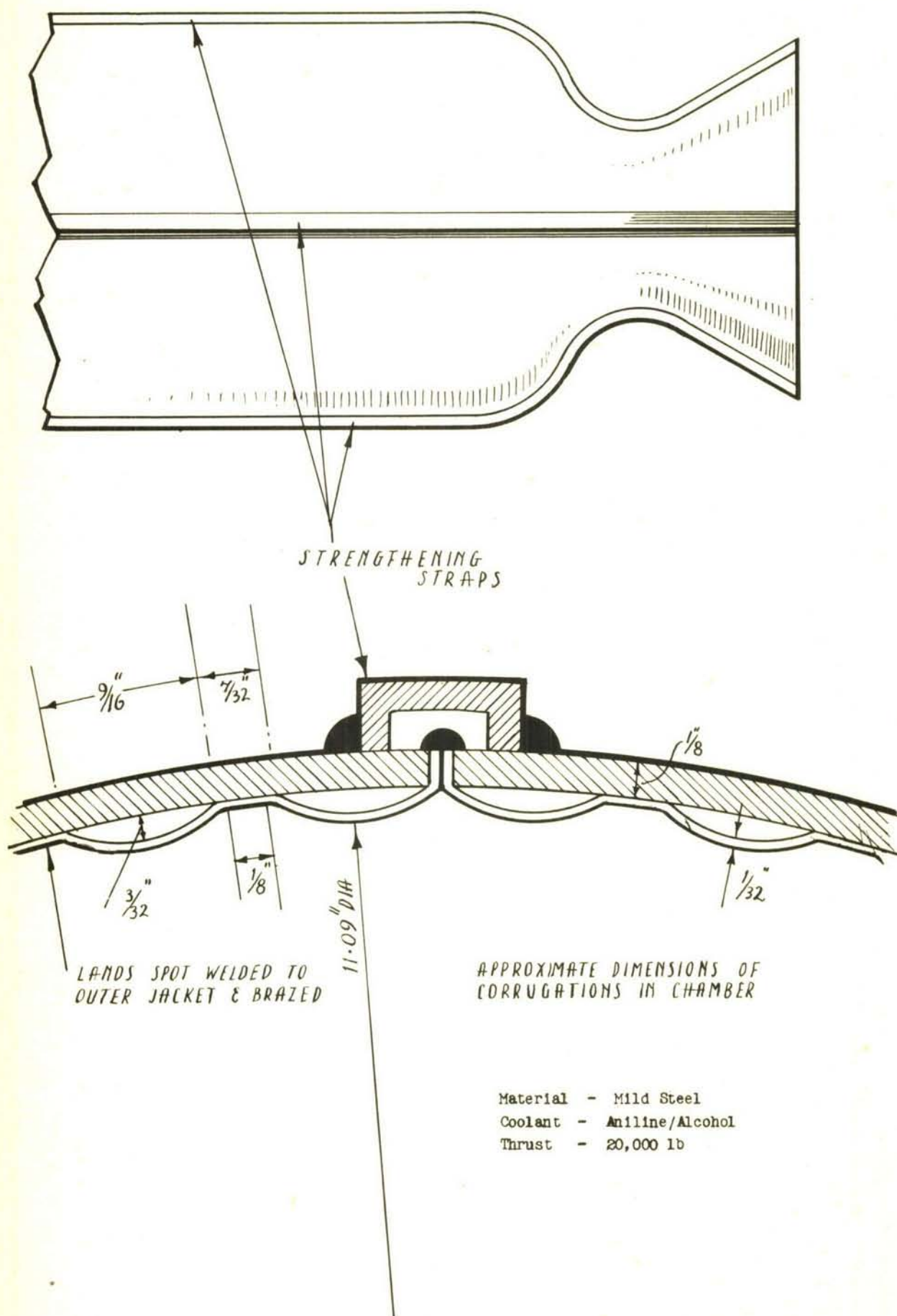


FIG. 11. CORPORAL "E" COMBUSTION CHAMBER
(JET PROPULSION LABORATORY)

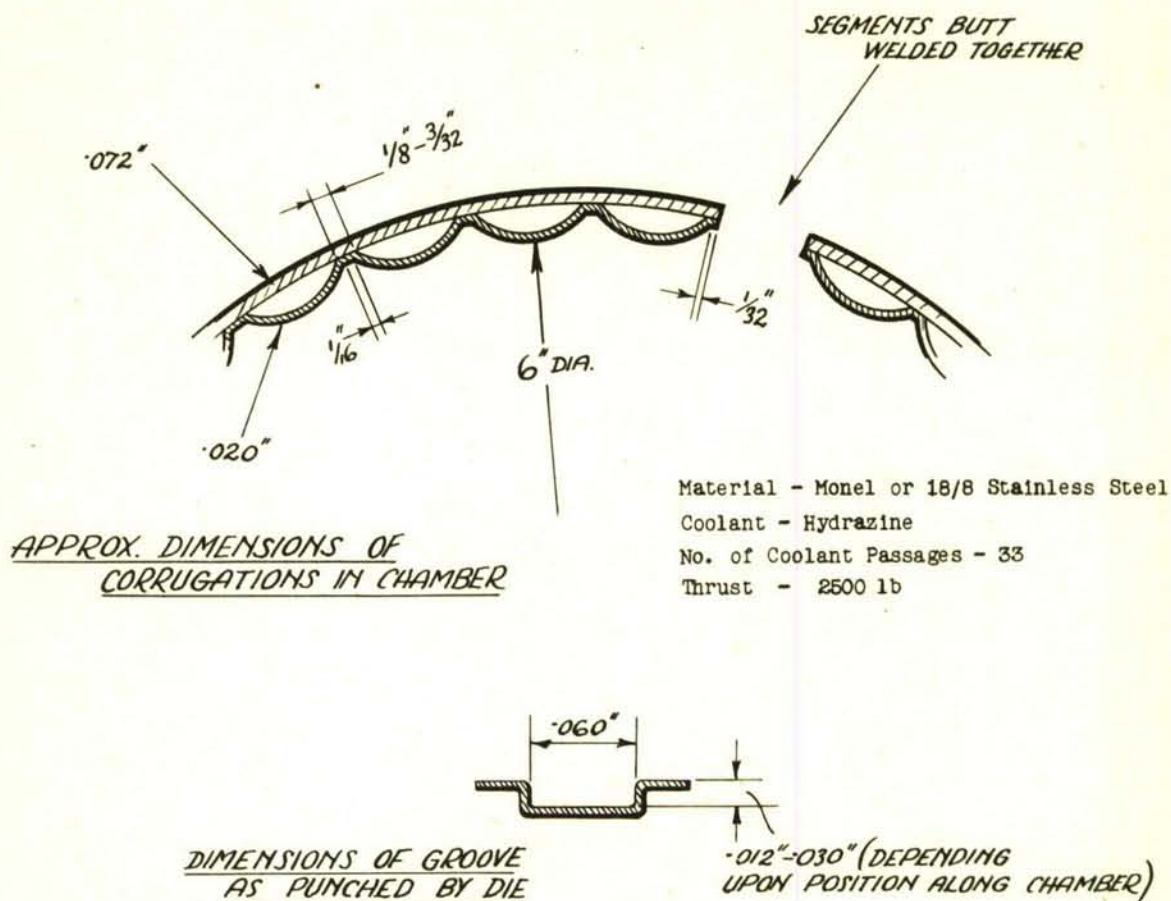
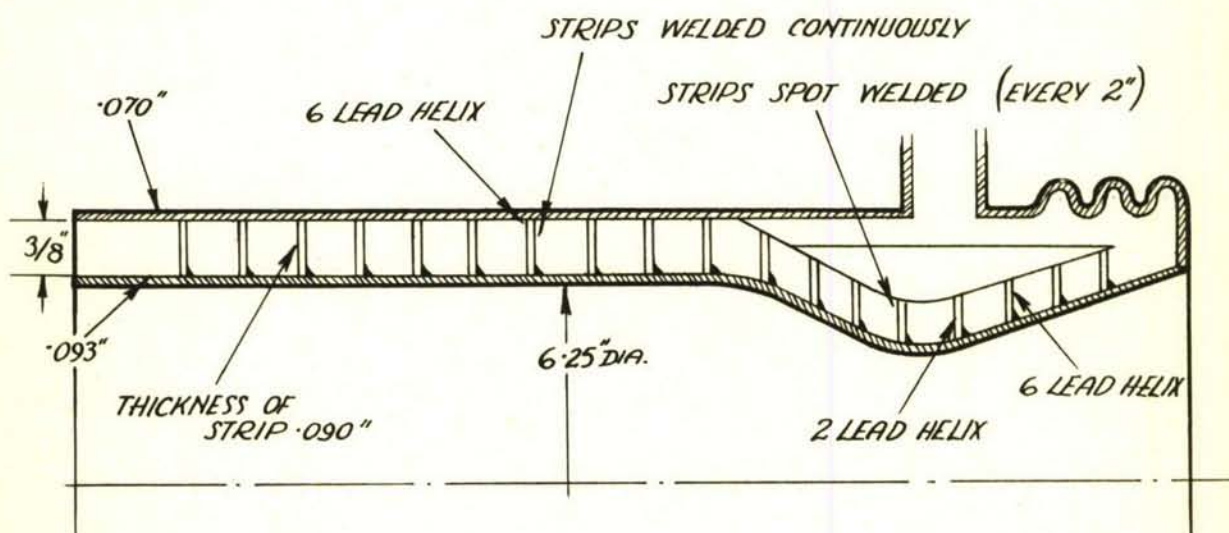


FIG.12. CORRUGATED CHAMBER FOR 2500 lb THRUST
(JET PROPULSION LABORATORY)



Coolant Velocity (Nitric Acid) - Throat 35 ft/sec, Chamber 20 ft/sec
Ratio of Chamber Dia/Throat - 1.9/1
L* - 45 in
Thrust - 5000 lb
Material - 18/8 Stainless Steel

FIG.13. CHAMBER FOR A.T.O. MOTOR
(AEROJET ENGINEERING Co.)

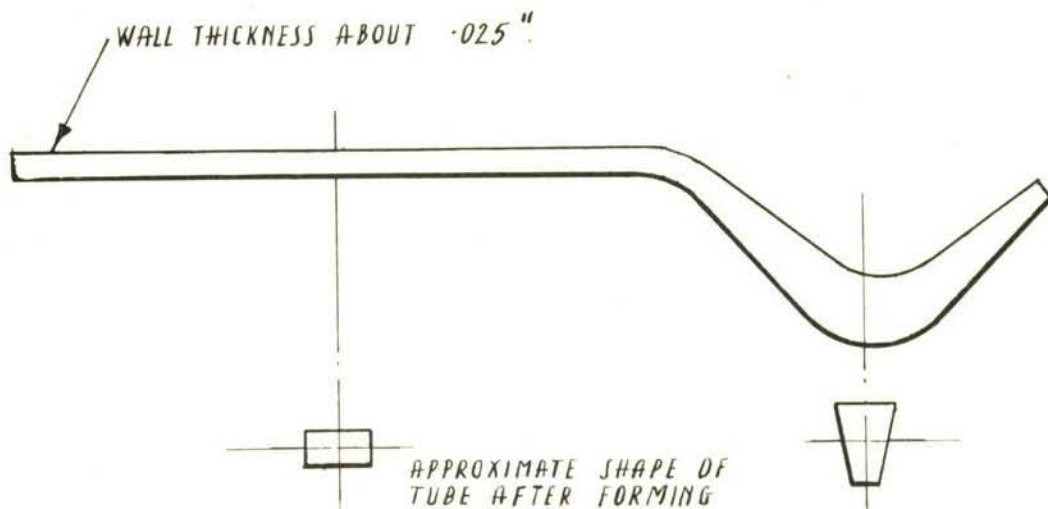
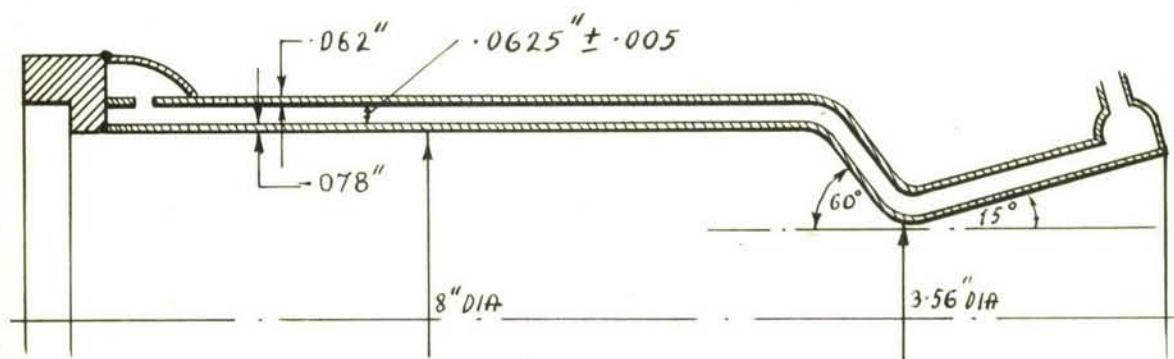
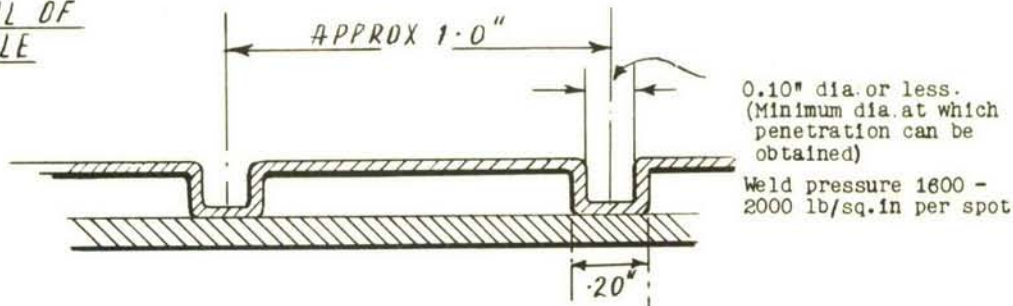


FIG. 14. TUBE FOR "SPAGHETTI" CHAMBER
(REACTION MOTORS, Inc.)



The outer jacket is welded to the inner jacket through a series of dimples punched in the outer jacket

DETAIL OF DIMPLE



Coolant (Nitric Acid) Velocity - Throat 40 ft/sec, Chamber 25 ft/sec
Coolant Pressure Drop - 100 lb/sq.in at 5000 lb thrust
Thrust - 5000 lb L^* - 70 in
Ratio of Chamber Dia/Throat Dia = $2\frac{1}{4}/1$
Material - 18/8 Stainless Steel (Type 347)

FIG. 15. CHAMBER FOR A.T.O. MOTOR
(M. W. KELLOG Co.)